Computational Modeling of Meteor-Generated Ground Pressure Signatures

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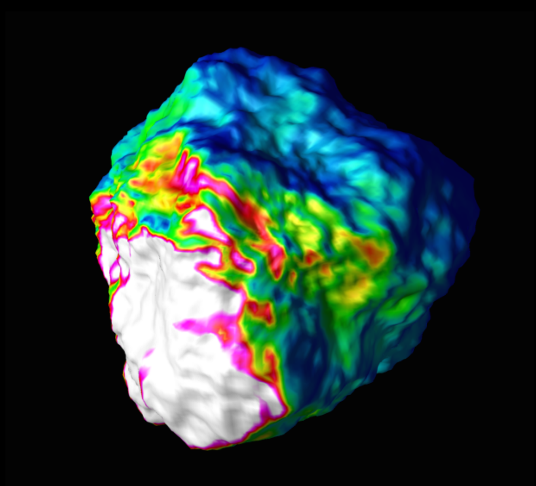
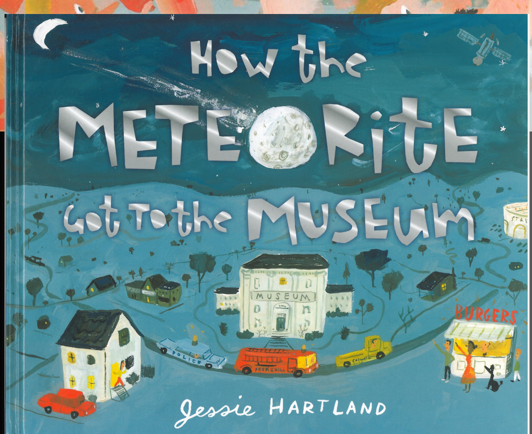


AMS Seminar Series
NASA Ames Research Center
July 6, 2017



Jessie Hartland, "How the Meteorite Got To the Museum", Blue Apple Books, 2013

Peekskill Meteorite (Oct. 9, 1992)

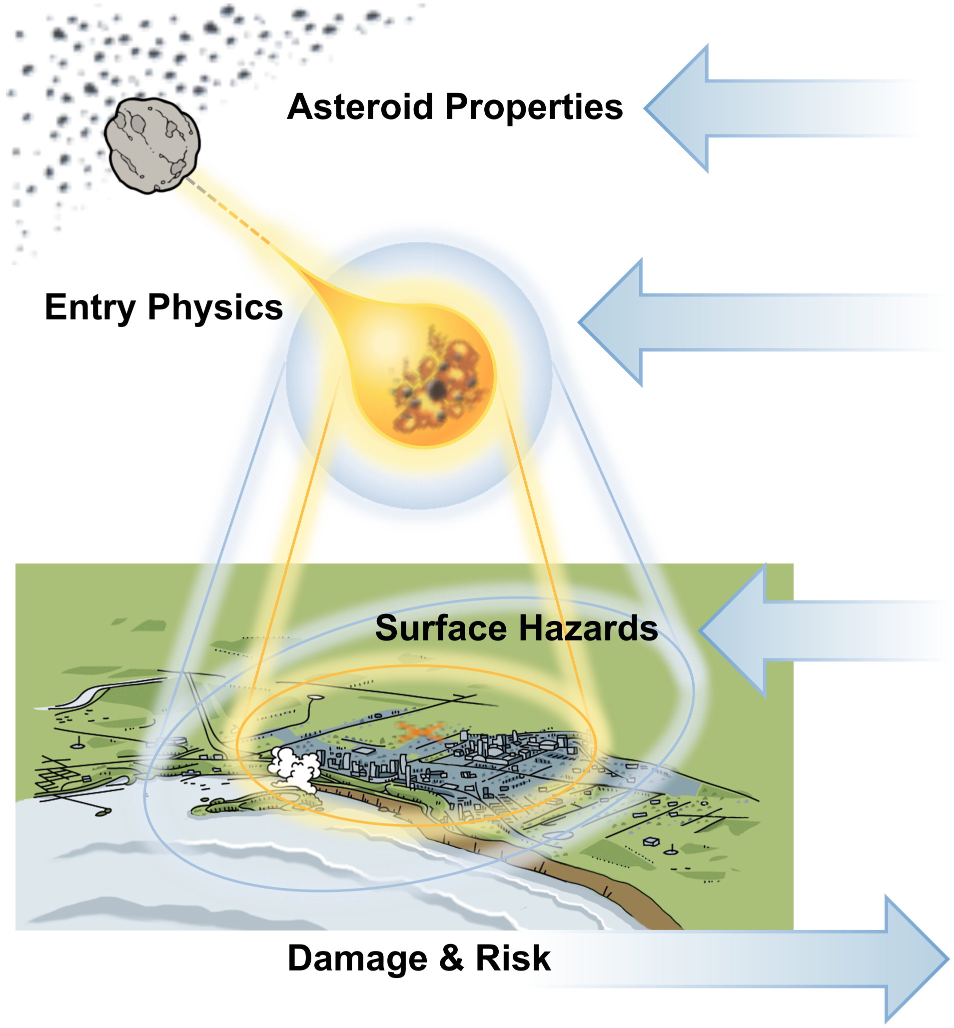
Peekskill Meteorite Fall, YouTube (www.youtube.com/watch?v=4_orvF9bLZg)

Peekskill Meteorite (Oct. 9, 1992)

ATAP Overview

Ames Research Center

Asteroid Threat Assessment



Characterization
- Measurements
- Inference
- Data aggregation
- Property database website

Entry Simulations & Testing
- Coupled aerothermodynamics
- Ablation & radiation modeling
- Arc jet testing

Hazard Simulations
- 3D blast simulations
- Impact crater simulations
- Tsunami simulations
- Thermal radiation models
- Global effects

Probabilistic Risk Assessment
- Analytic physics-based entry and damage models
- Probabilistic Monte Carlo simulation using uncertainty distributions

June 2017 Page 2

from the "Asteroid Threat Assessment Project" presentation to Small Bolide Assessment Group

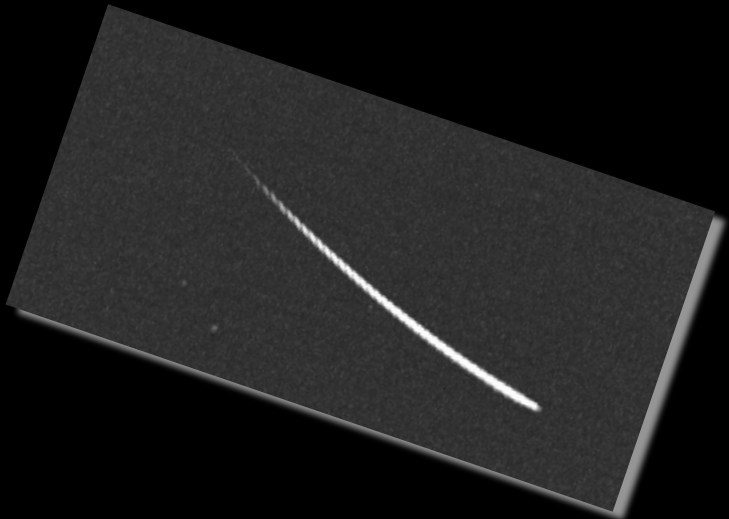
Motivation

- Meteors: steady source of infrasound
  - Meteoroid speed: 11-73 km/s
  - Meteoroid size: mm - m's
  - Strong bow-shock and complex flowfield

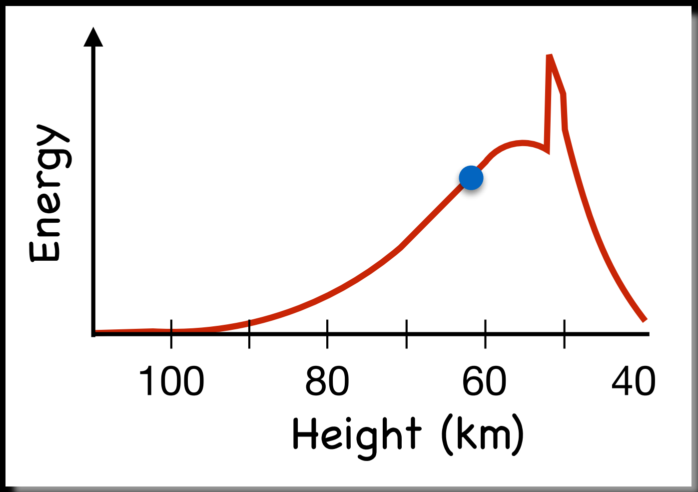
- Infrasound-based mass estimates help verify optical and radar observations
  - Independent of ablation process
  - Avoids pitfalls of estimating luminous and ionization efficiencies
- Low attenuation in the atmosphere
  - Signal propagates well

Motivation

- Exclusive reliance on analytic models to interpret meteoric infrasound
  - Blast-wave theory, weak nonlinear then linear wave propagation (ReVelle, 1976)
  - Frequently used but poorly validated



- New constrained dataset (Silber, 2014)
  - Coordinated optical and infrasound measurements
    - Elginfield Infrasound Array (ELFO)
    - Southern Ontario Meteor Network (SOMN)
  - Analytic model validation shows significant variability in mass estimates (10x)



- Can numerical models do better?
  - Relax assumptions needed in analytic models
  - Promising numerical simulations of Henneton *et al.*, 2015

Objectives

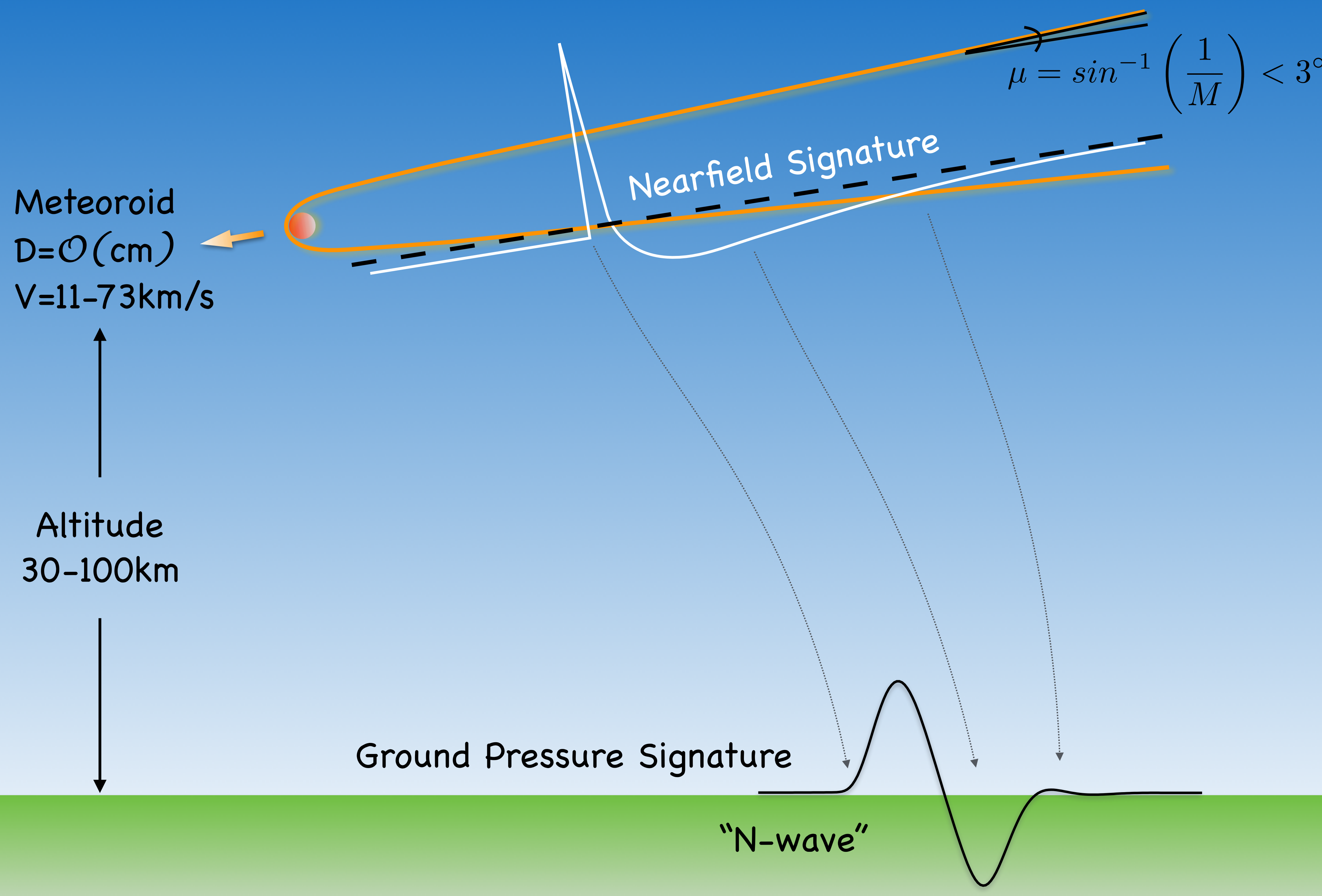
Validate computational prediction of regional meteoric infrasound

Given photometric data of meteor begin and end points determine ground signature and propagation time

Develop a numerical model appropriate for predicting meteor-generated infrasound → Use ELFO dataset to validate proposed numerical model

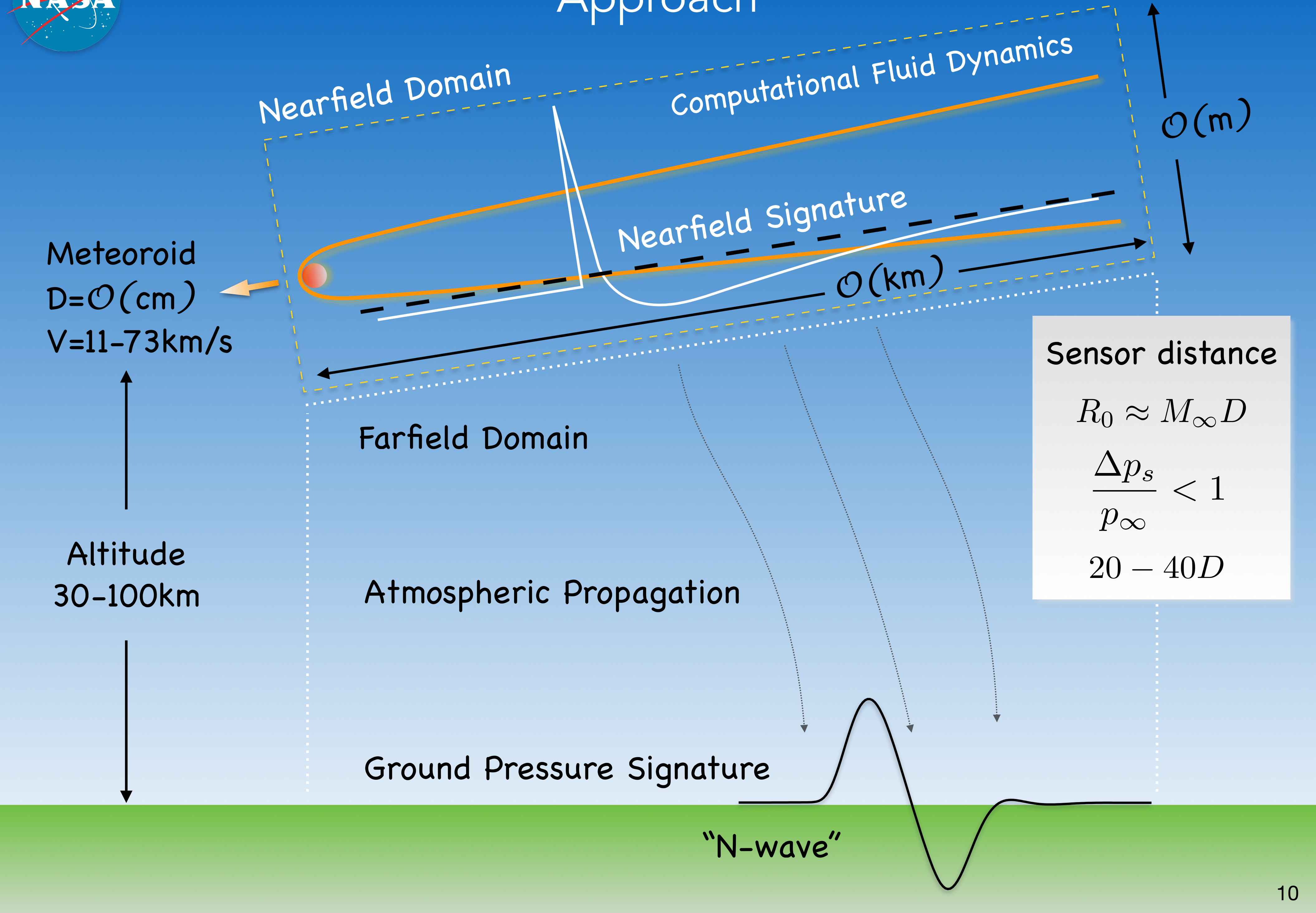
- Assumptions
  - Energy deposition dominated by drag
  - Single-body meteoroids
- Goals
  - Validate photometric mass estimates
  - Study the relationship between pressure signature and meteoroid flight characteristics

Approach



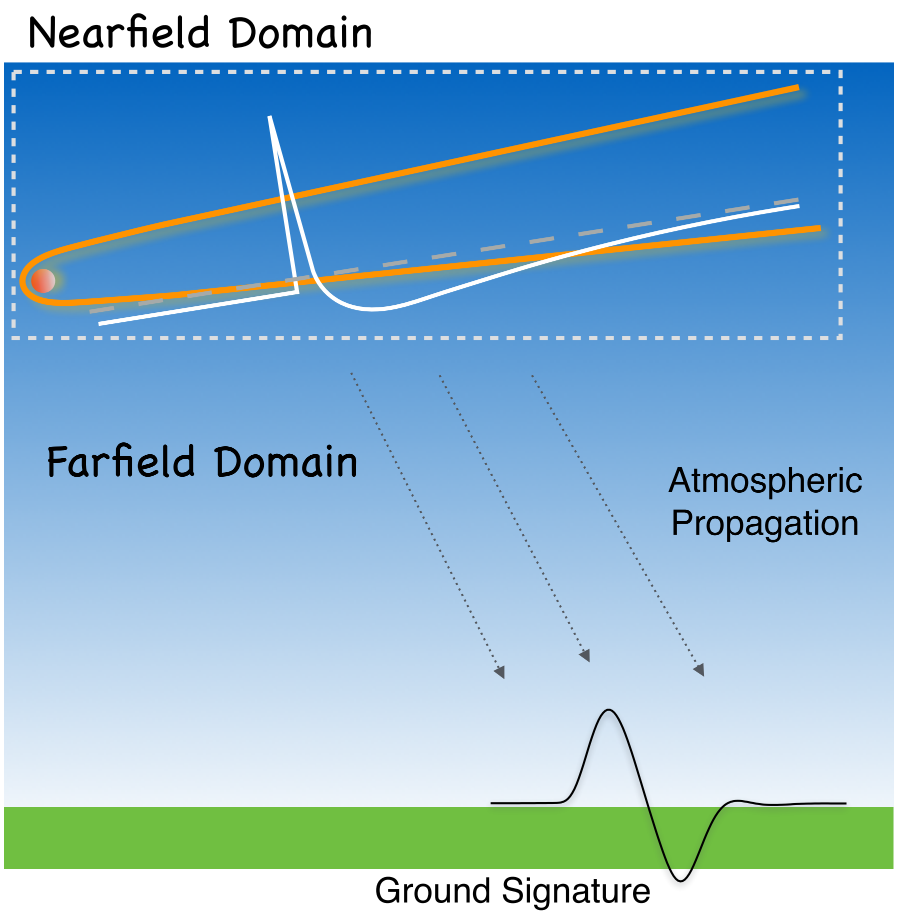
Meteoroid
D=$\mathcal{O}$(cm)
V=11-73km/s
Altitude
30-100km
$\mu = sin^{-1}\left(\frac{1}{M}\right) < 3°$
Nearfield Signature
Ground Pressure Signature
"N-wave"

Approach

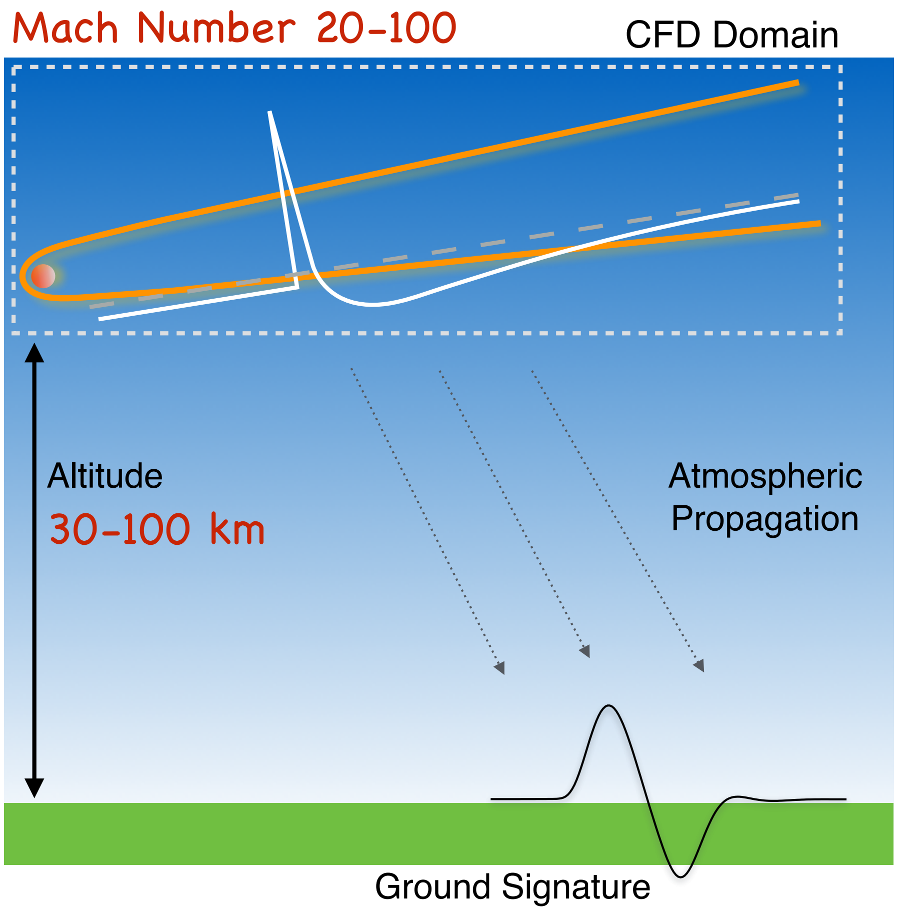


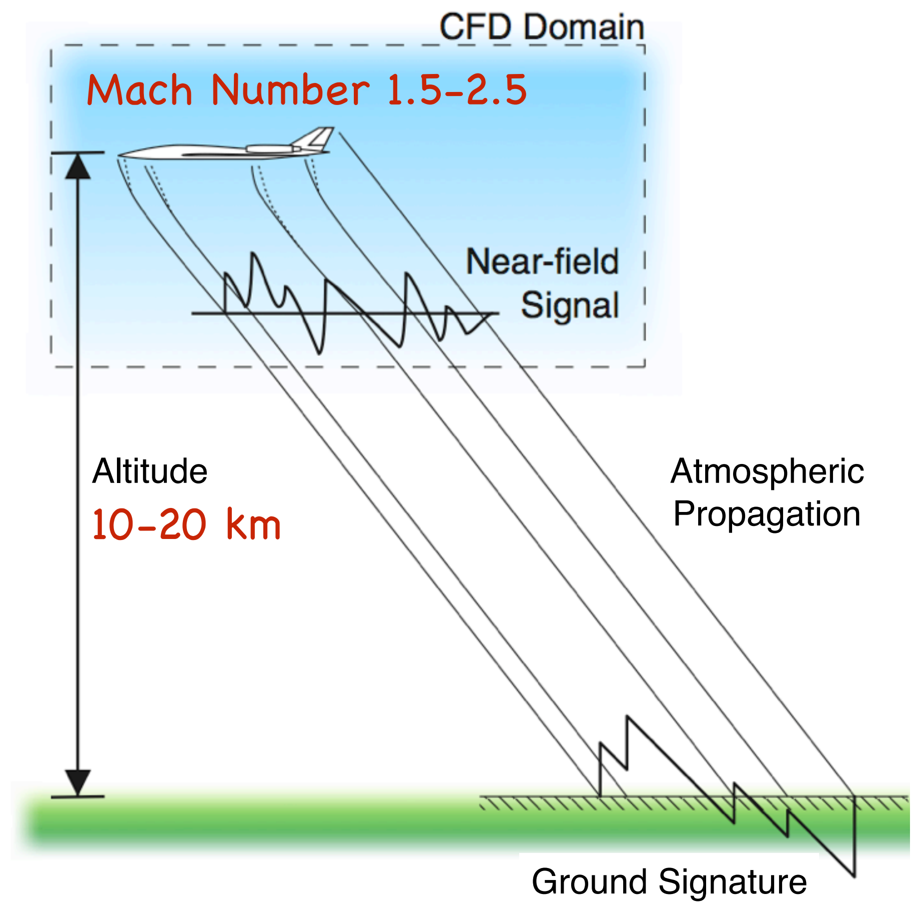
Nearfield Domain
Computational Fluid Dynamics
$\mathcal{O}(m)$
Nearfield Signature
$\mathcal{O}(km)$
Meteoroid
$D=\mathcal{O}(cm)$
V=11-73km/s
Altitude
30-100km
Farfield Domain
Atmospheric Propagation
Ground Pressure Signature
"N-wave"
Sensor distance
$R_0 \approx M_\infty D$
$\frac{\Delta p_s}{p_\infty} < 1$
$20 - 40D$

Approach


Nearfield Domain
Farfield Domain
Atmospheric
Propagation
Ground Signature

Approach





Typical overpressure < 1 Pa

Typical overpressure > 10 Pa

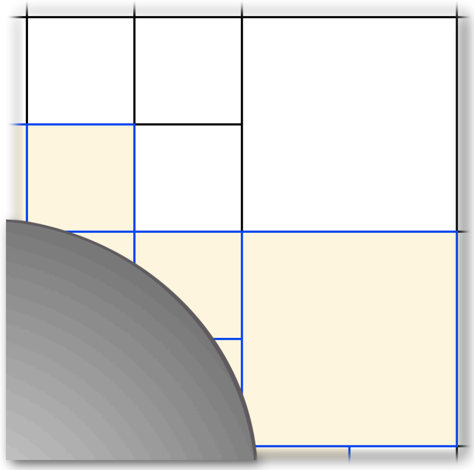
Leverage tools and experience from aircraft sonic-boom analysis and low-boom design

Nearfield Solver: Cart3D

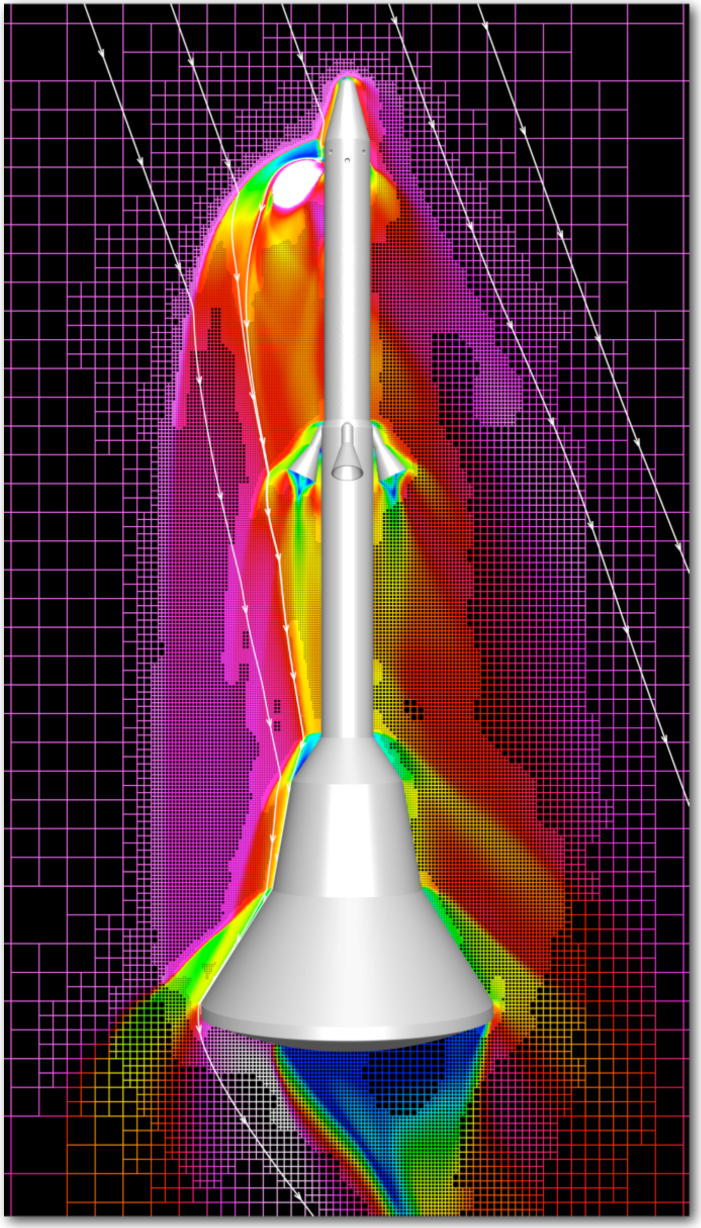
Assumptions

- Air in thermochemical equilibrium
- Steady inviscid flow
  - Euler equations

Flow Simulation

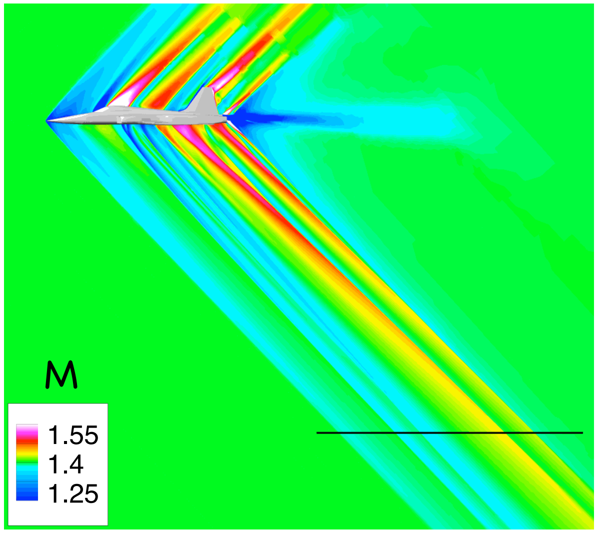


- Cartesian mesh with cut cells
- Second-order finite-volume spatial discretization
- Adaptive mesh refinement
  - Method of adjoint weighted residuals: mesh tailored to minimize discretization error in selected outputs
- Broad use throughout NASA, US Government, industry and academia



www.nas.nasa.gov/publications/software/docs/cart3d

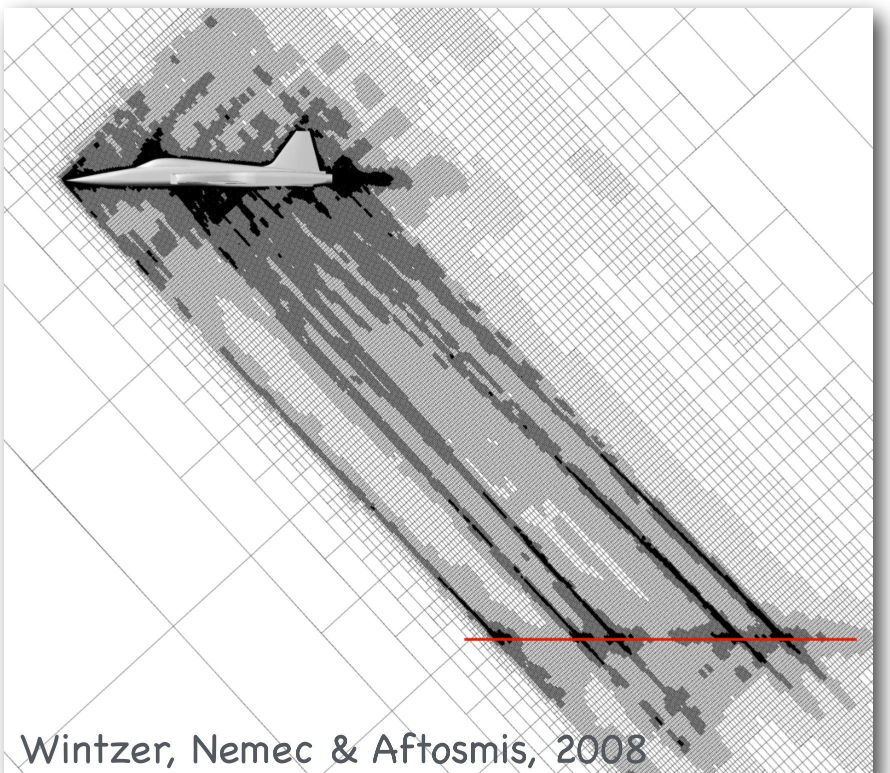
Nearfield Signature Prediction with Cart3D

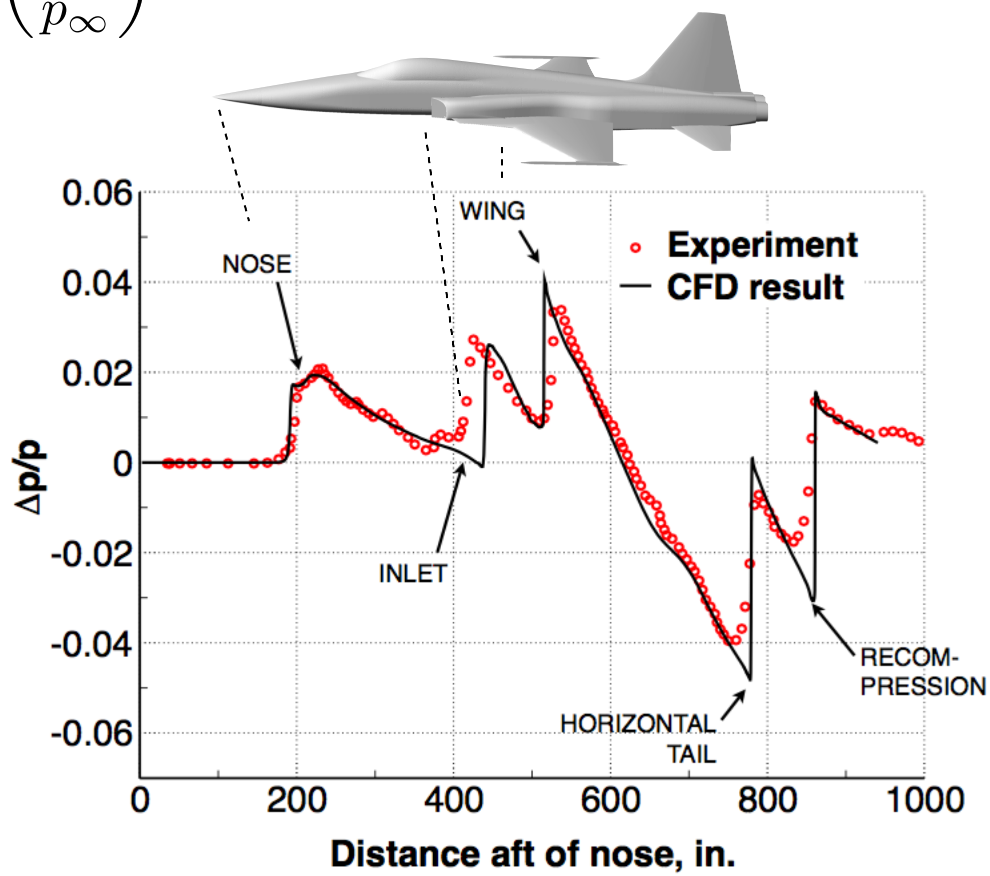


F5-E Nearfield Pressure Flight Test

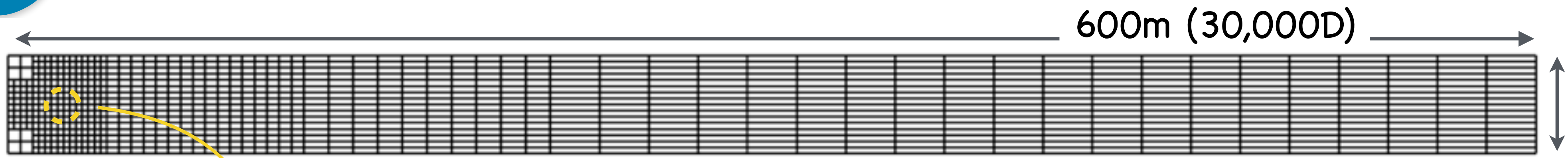
- Mach number 1.4
- Separation distance is roughly 2 aircraft lengths
- Output of interest is the aircraft's pressure signature

$$J = \int_0^L \left(\frac{\Delta p}{p_\infty}\right)^2 ds$$

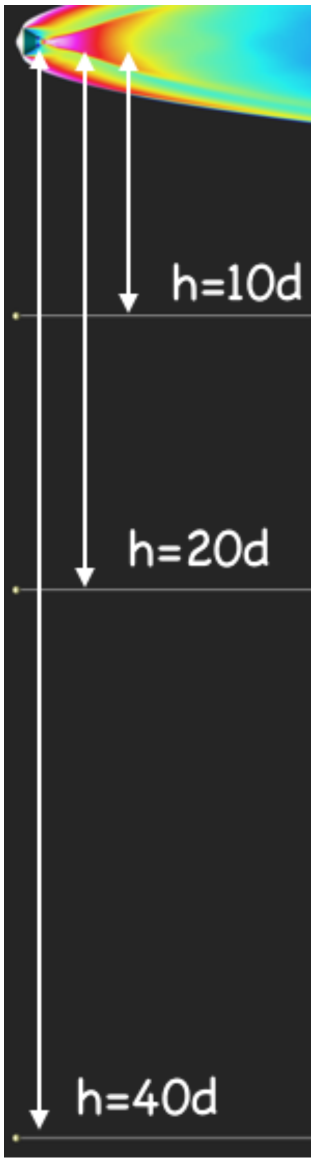


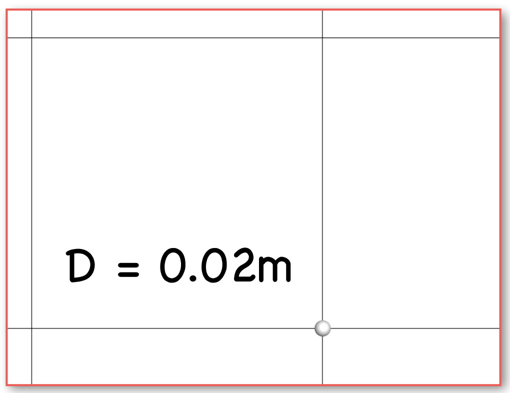


Meteoroid Simulation Setup



20m
(1,000D)





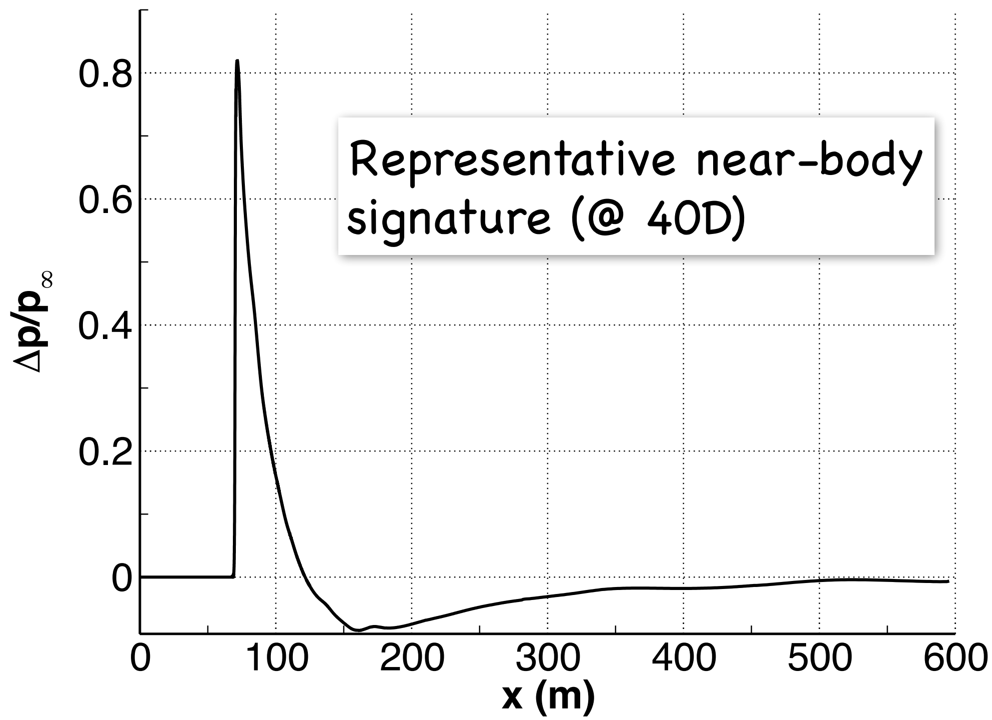
Anisotropic Cartesian background mesh with pre-specified cell stretching

Signature extraction distance requires shock overpressure ratio < 1

$$R_0 \approx M_\infty D$$

Pressure signature functional:

$$J = \int_0^L \left(\frac{\Delta p}{p_\infty} \right)^2 ds$$

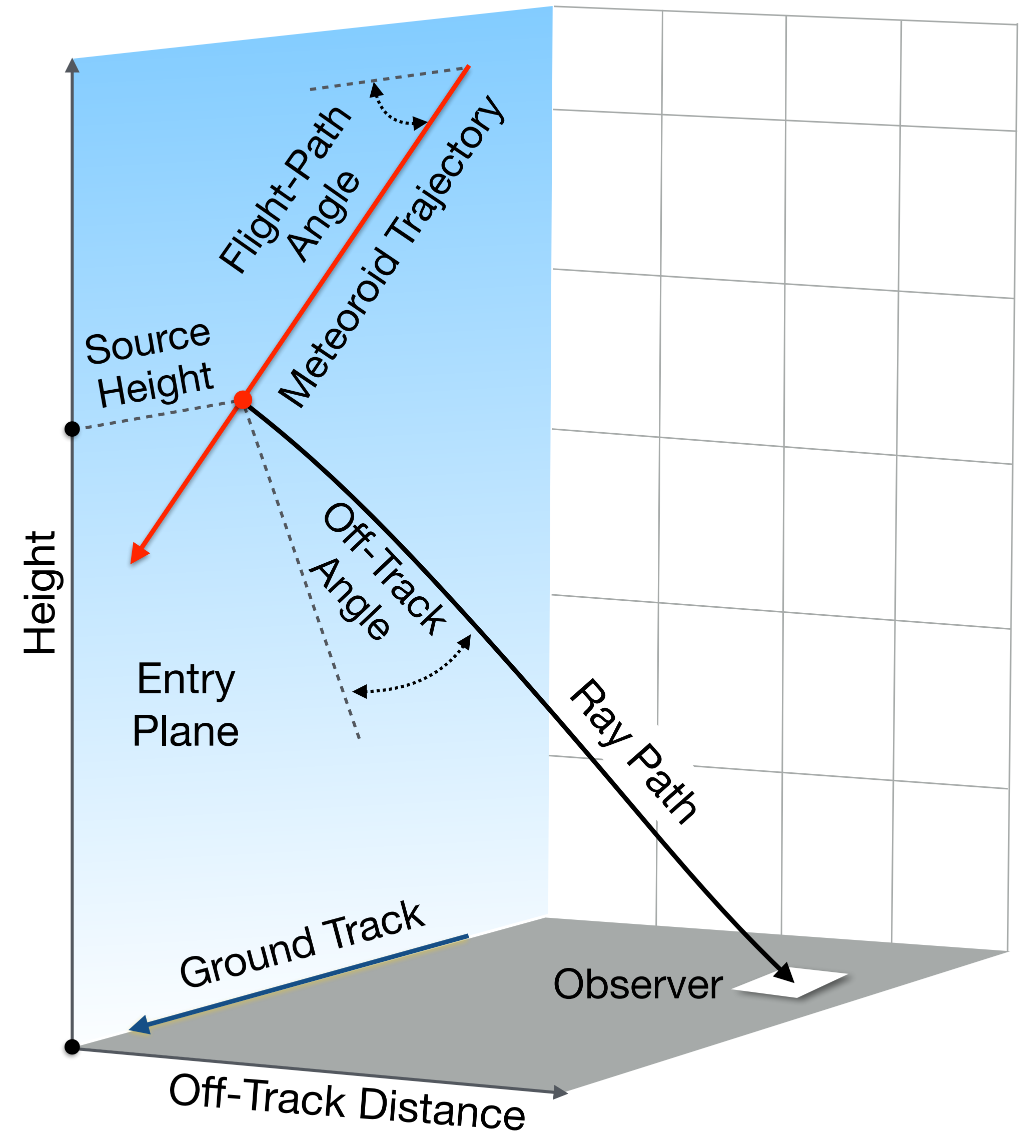


Avoid premature truncation of the pressure recovery region

Farfield Signal Propagation: sBOOM

1) Find source height of signature by minimizing travel time residual

2) Propagate Waveform

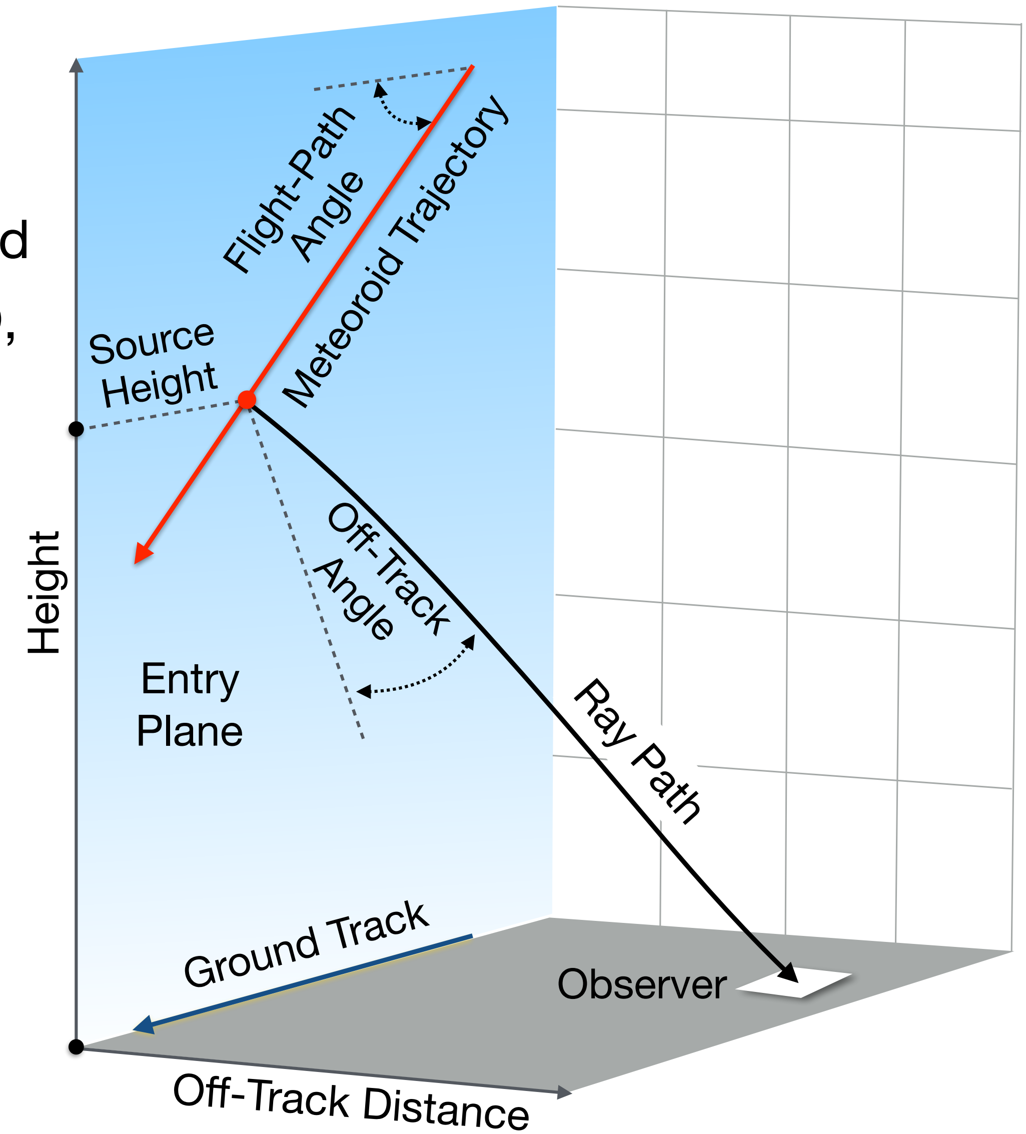


Rallabhandi, J. Aircraft, 2011

Farfield Signal Propagation: sBOOM

1) Find source height of signature by minimizing travel time residual

- Ray tracing via geometric acoustics
- Requires accurate temperature and wind profiles (ground weather station, UKMO, HWM95, NRL-MSIS00)
- Primary signature only



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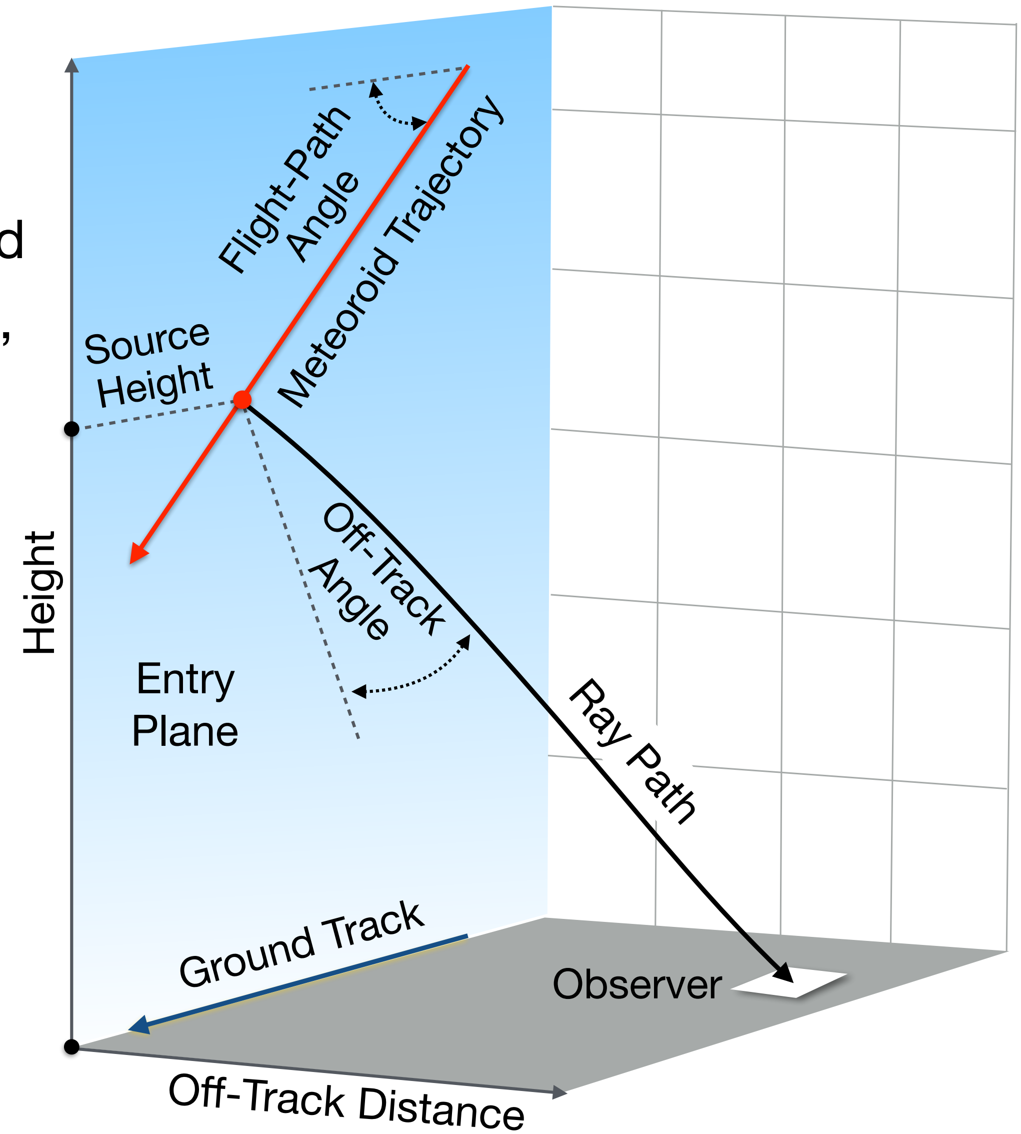
Farfield Signal Propagation: sBOOM

1) Find source height of signature by minimizing travel time residual

- Ray tracing via geometric acoustics
- Requires accurate temperature and wind profiles (ground weather station, UKMO, HWM95, NRL-MSIS00)
- Primary signature only

2) Propagate Waveform

- Quasi-1D formulation
- Augmented Burgers' equation
  - Nonlinear steepening
  - Thermoviscous absorption
  - Molecular relaxation
- Reative humidity ANSI S1.26
- No diffraction model



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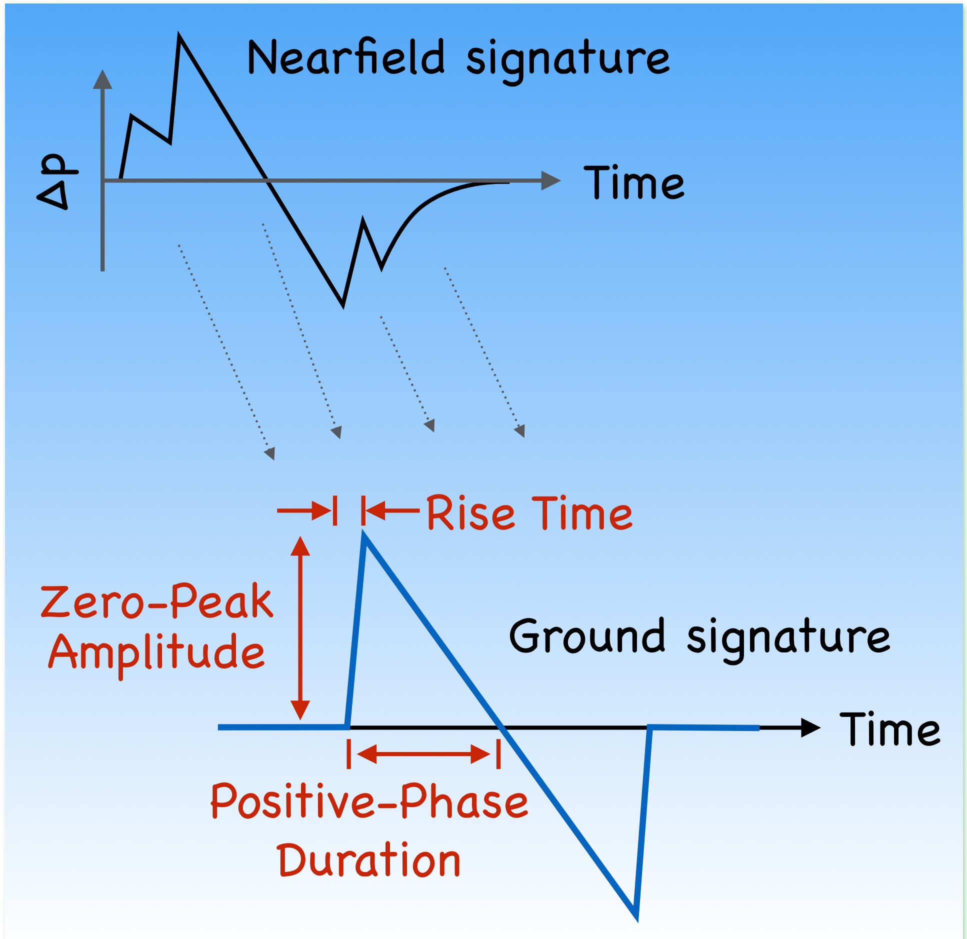
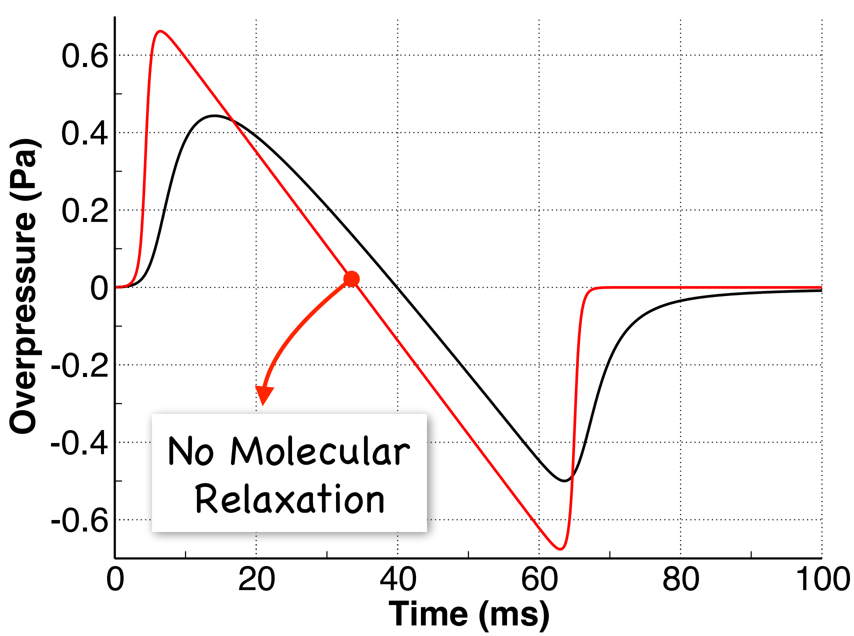
Farfield Signal Propagation: sBOOM



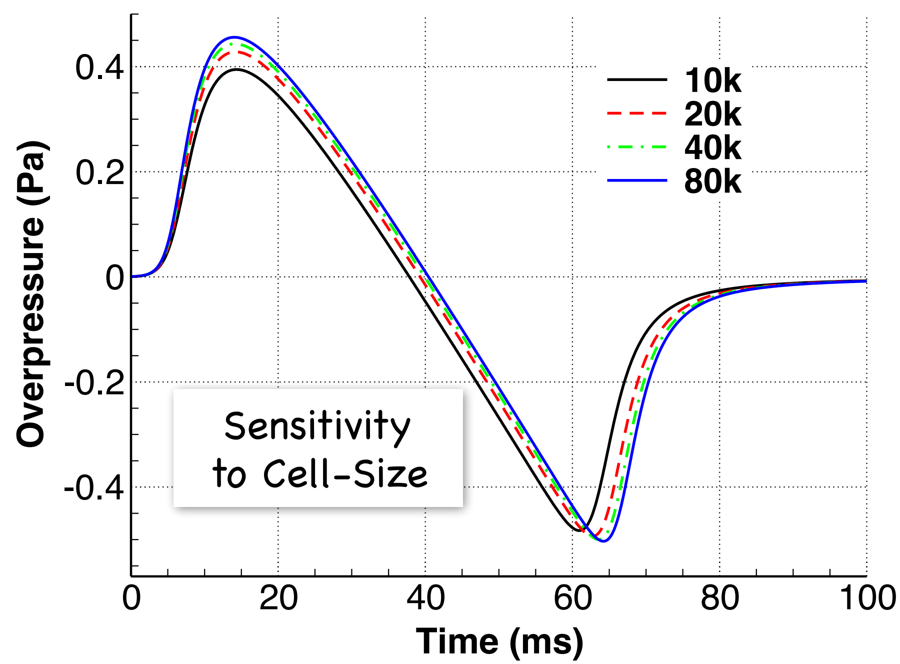
Primary Waveform Metrics

Farfield Signal Propagation: sBOOM

Molecular Relaxation Effects

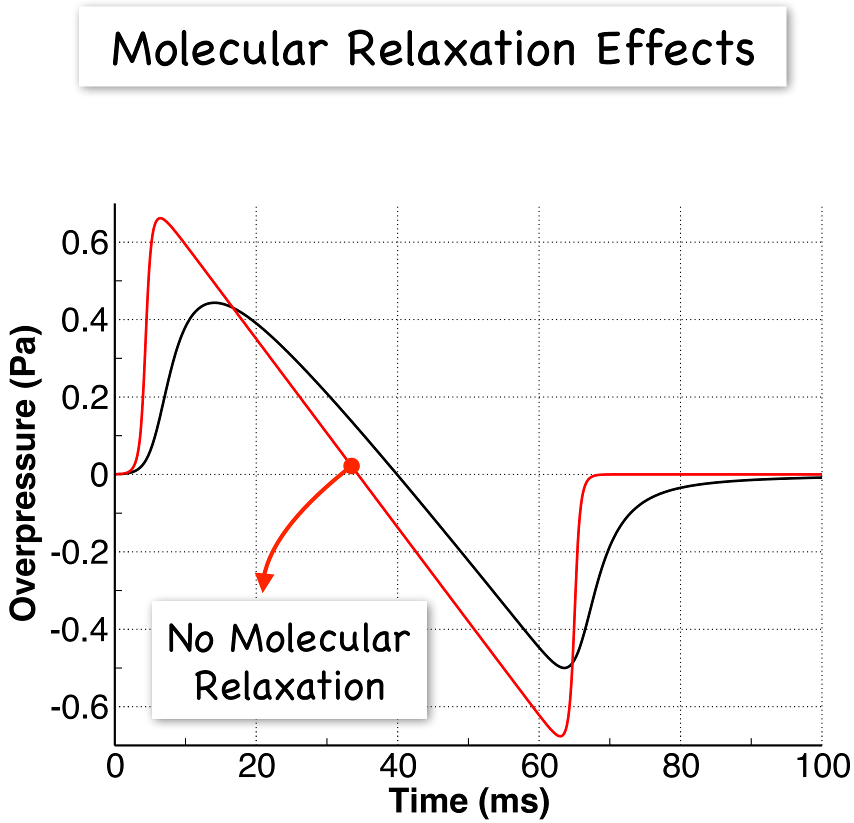


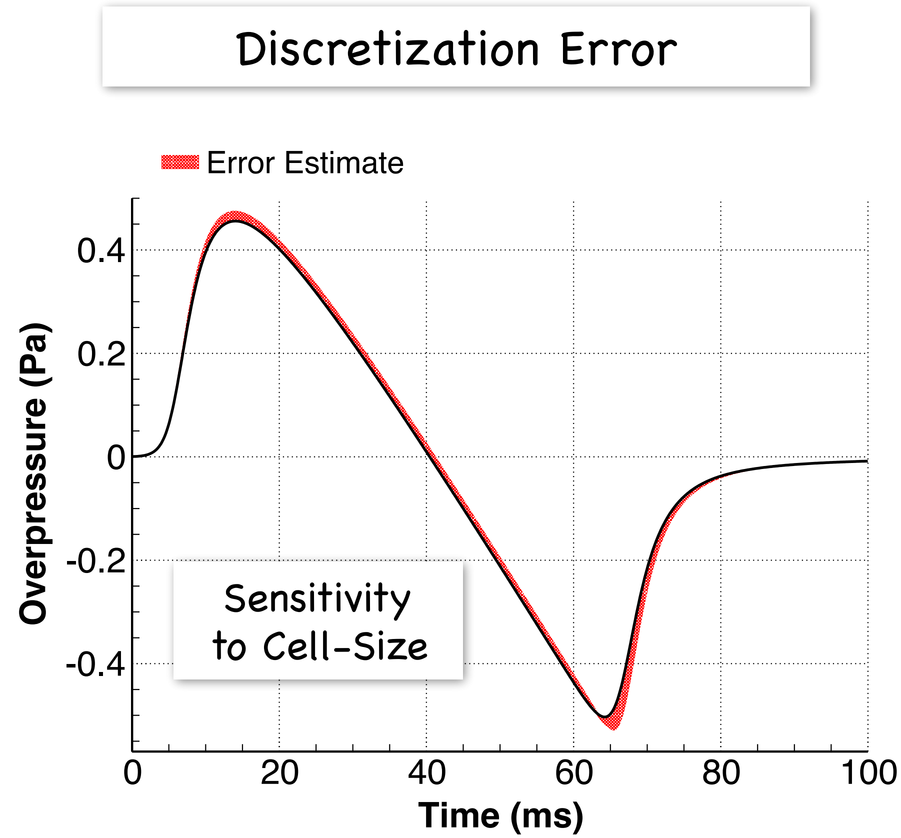
Discretization Error



Propagation from higher altitude and over longer range than aircraft sonic booms

Farfield Signal Propagation: sBOOM





Propagation from higher altitude and over longer range than aircraft sonic booms

Results

Part A. Stardust Entry

- NASA's artificial meteor (12.5 km/s)
- Well-defined geometry and trajectory

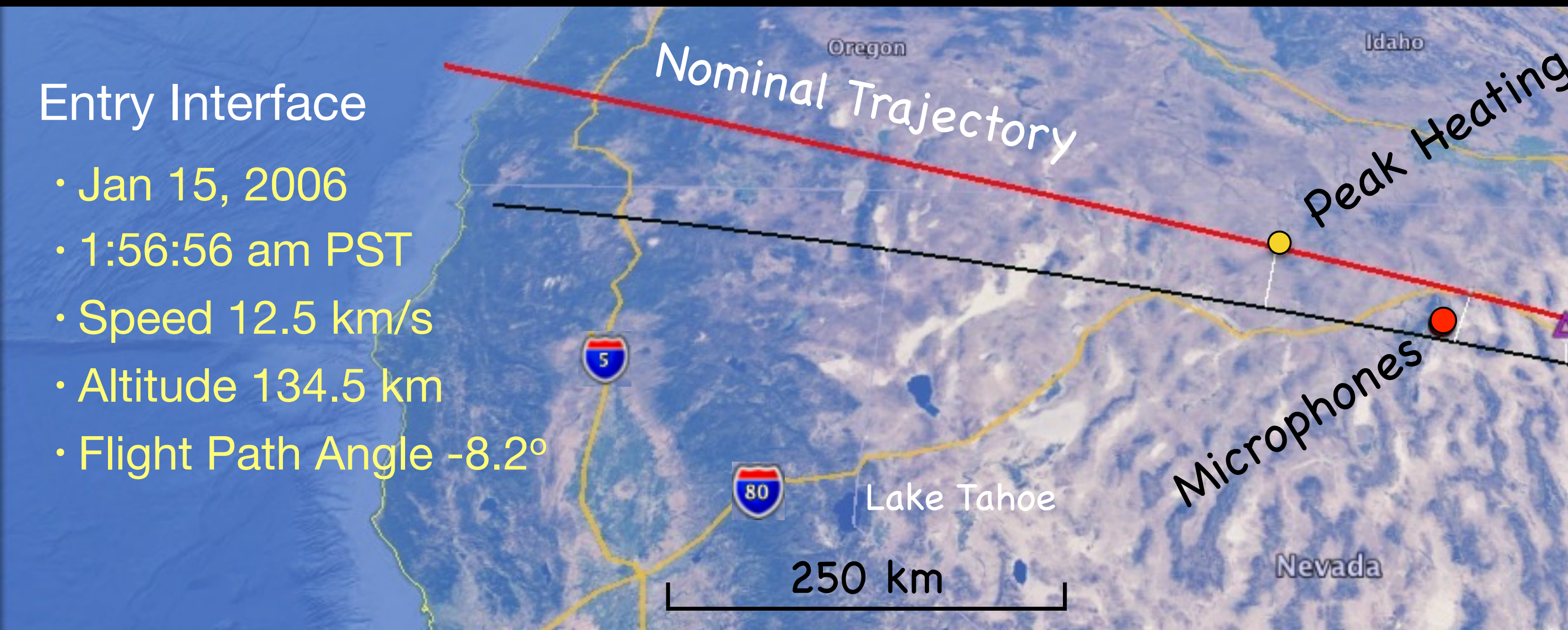
Part B. SOMN-ELFO Infrasound Dataset

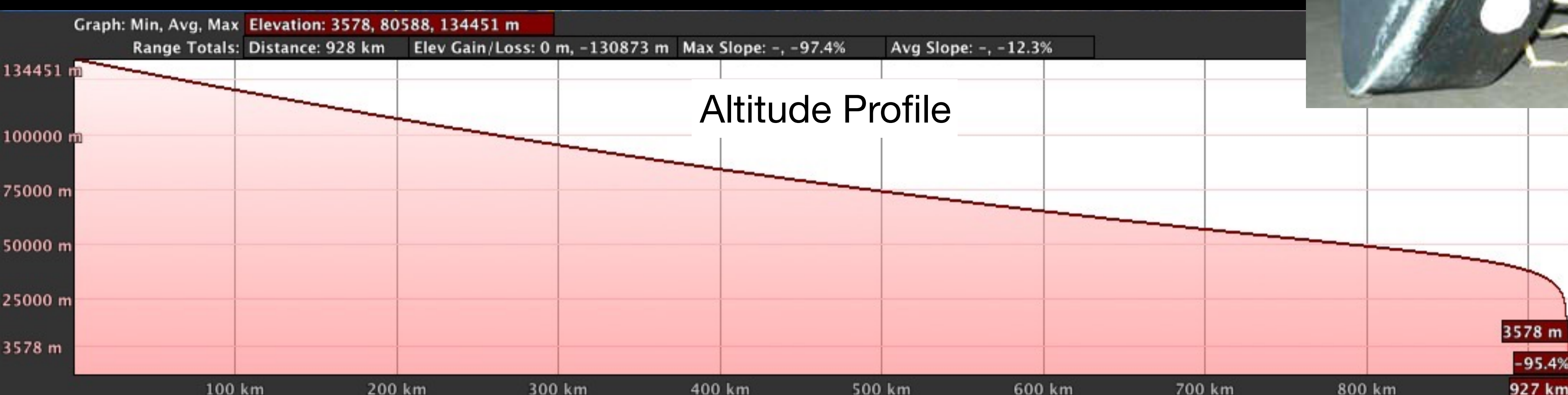
1. Meteor 20081028
    - Single infrasonic arrival
2. Meteor 20090428
    - Multiple arrivals
    - Steeper and faster entry

Stardust — Artificial Meteor

Entry Interface

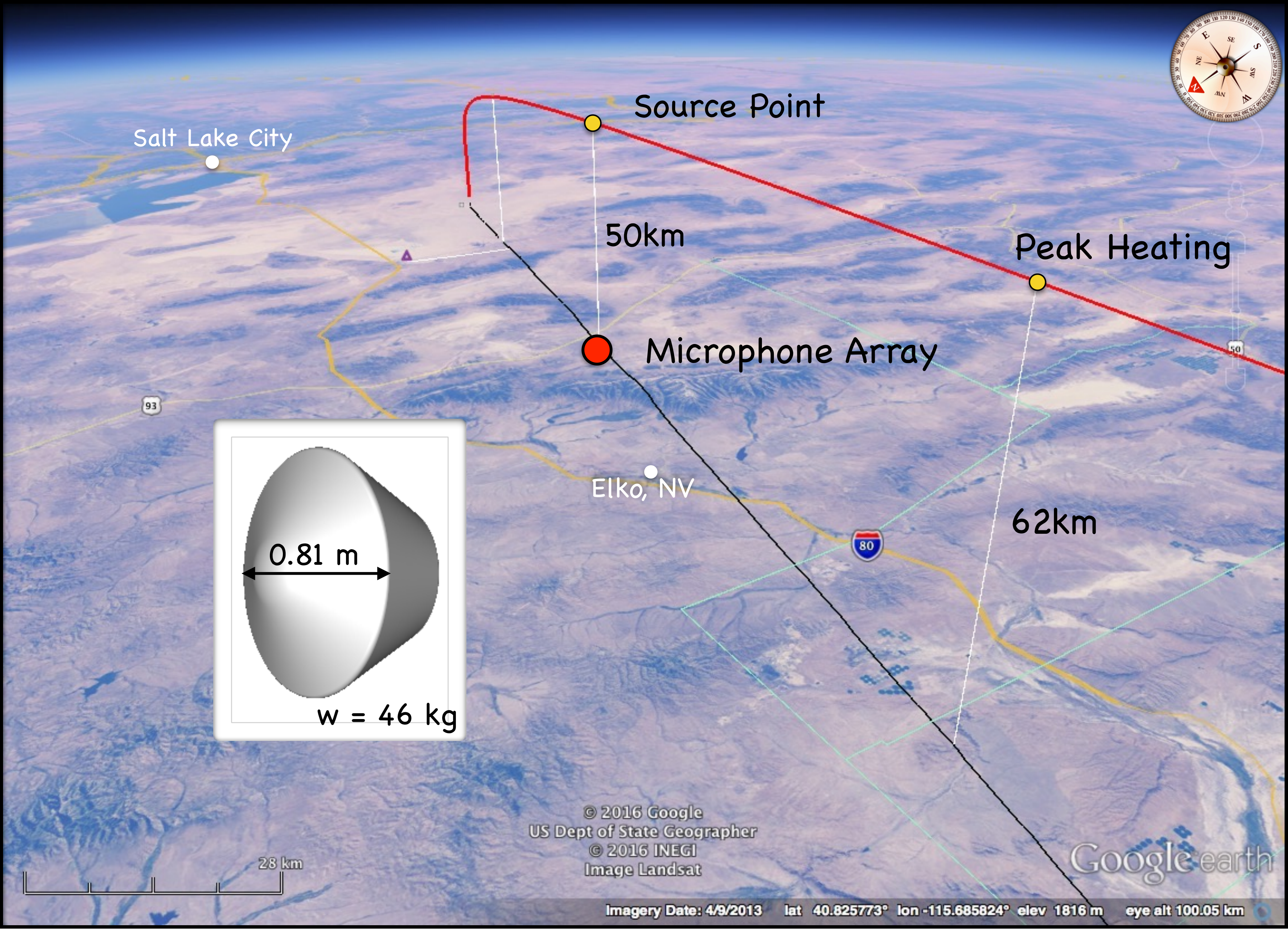
- Jan 15, 2006
- 1:56:56 am PST
- Speed 12.5 km/s
- Altitude 134.5 km
- Flight Path Angle -8.2°





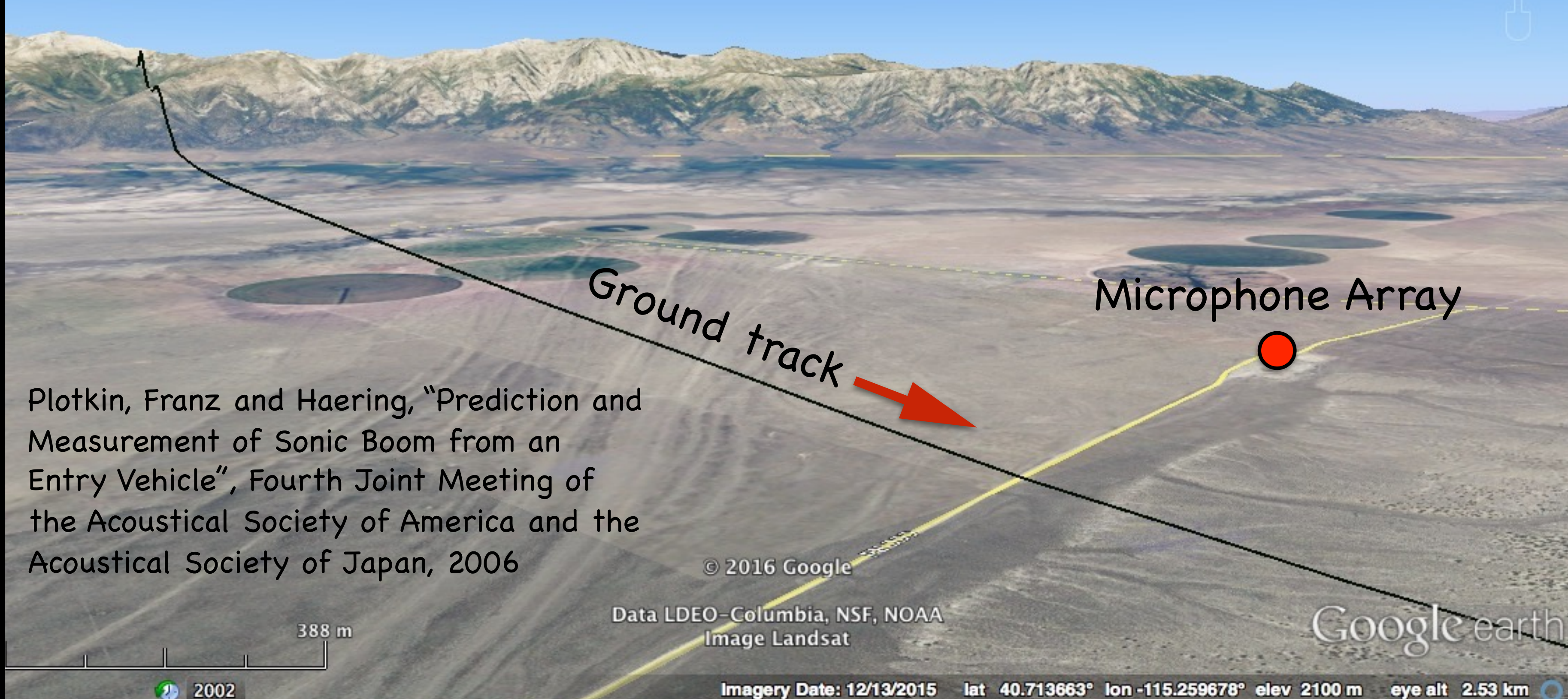
P. Desai, NASA Lanley, AIAA 2008-1198

Trajectory and Sensors



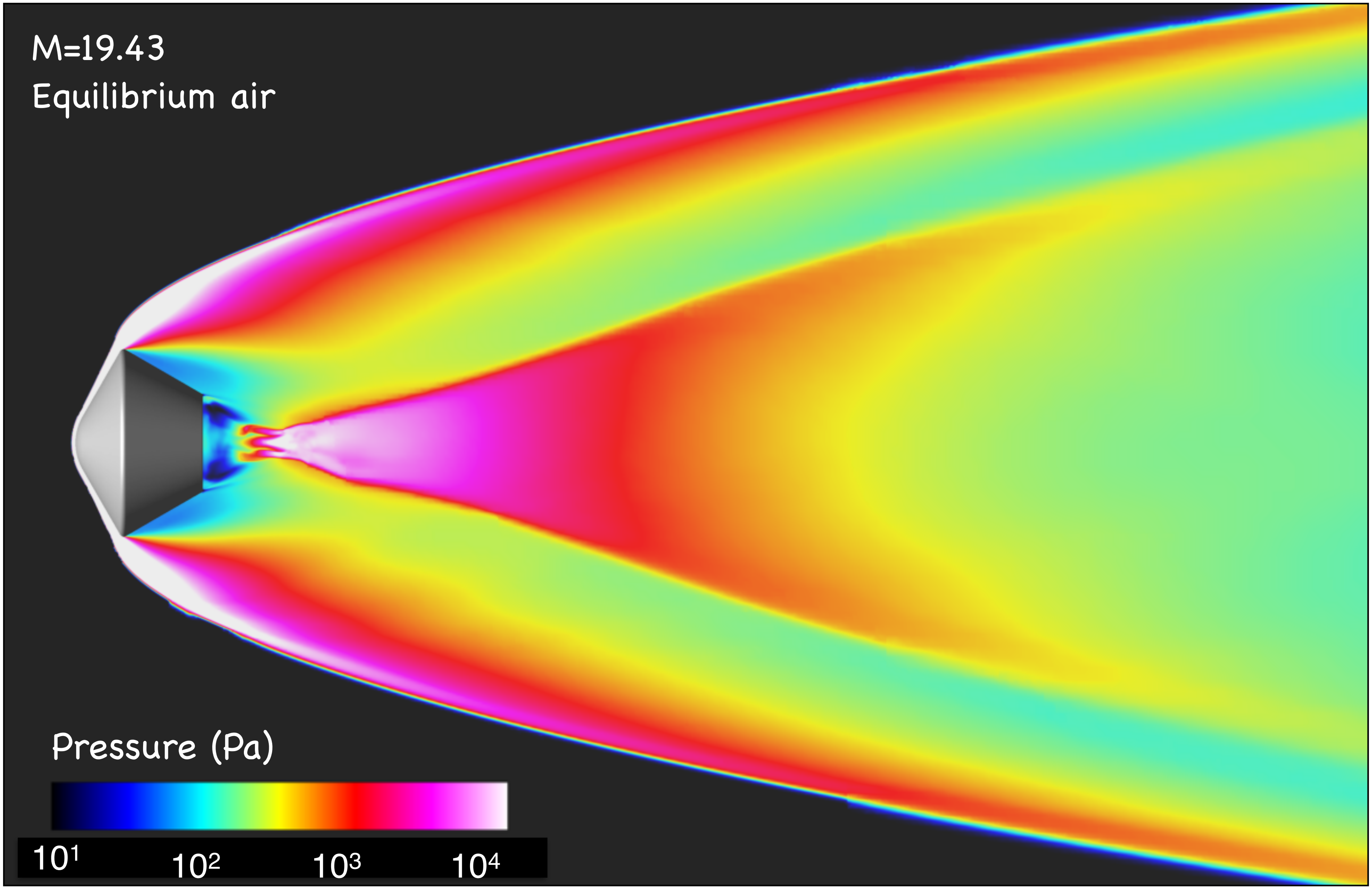
Microphone Array

- Edward A. Haering, James E. Murray and Russell Franz, Armstrong Flight Research Center
- Four B&K 4193 microphones
- Dactron LDS Focus II recorder, 24000 sps
- Location is essentially on-track
- Windy conditions with blowing snow at times
- **Source height 165,418 ft (50.4 km), M=19.43 (6.4 km/s)**

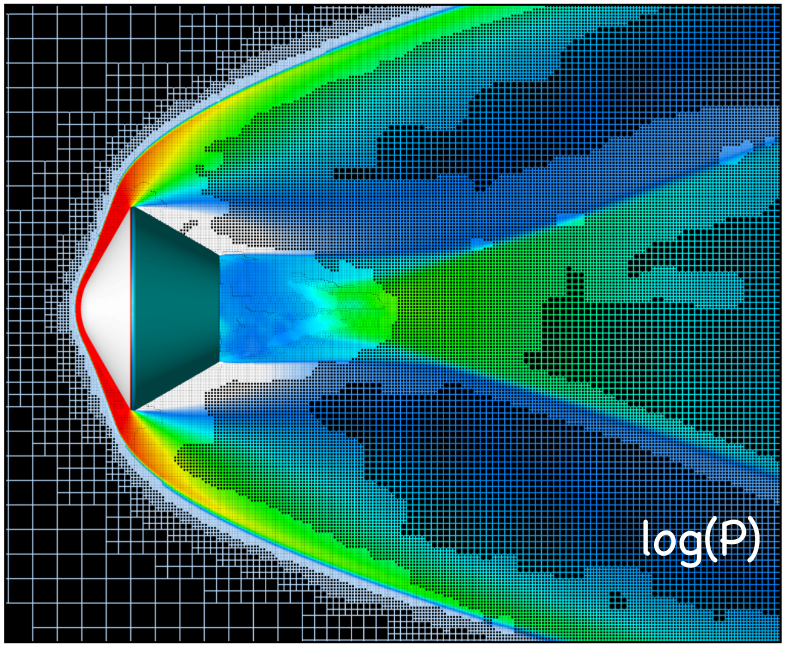


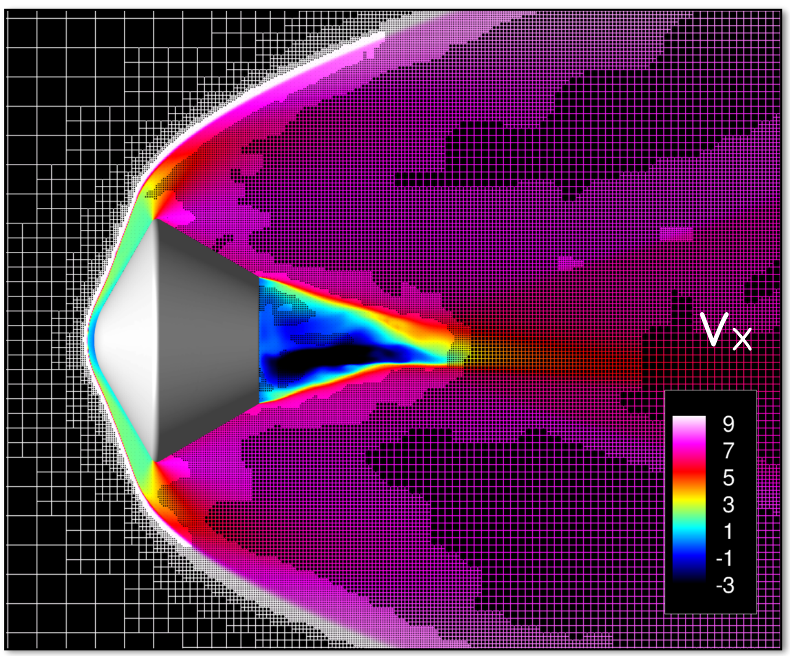
Plotkin, Franz and Haering, "Prediction and Measurement of Sonic Boom from an Entry Vehicle", Fourth Joint Meeting of the Acoustical Society of America and the Acoustical Society of Japan, 2006

Near-Body Pressure Contours

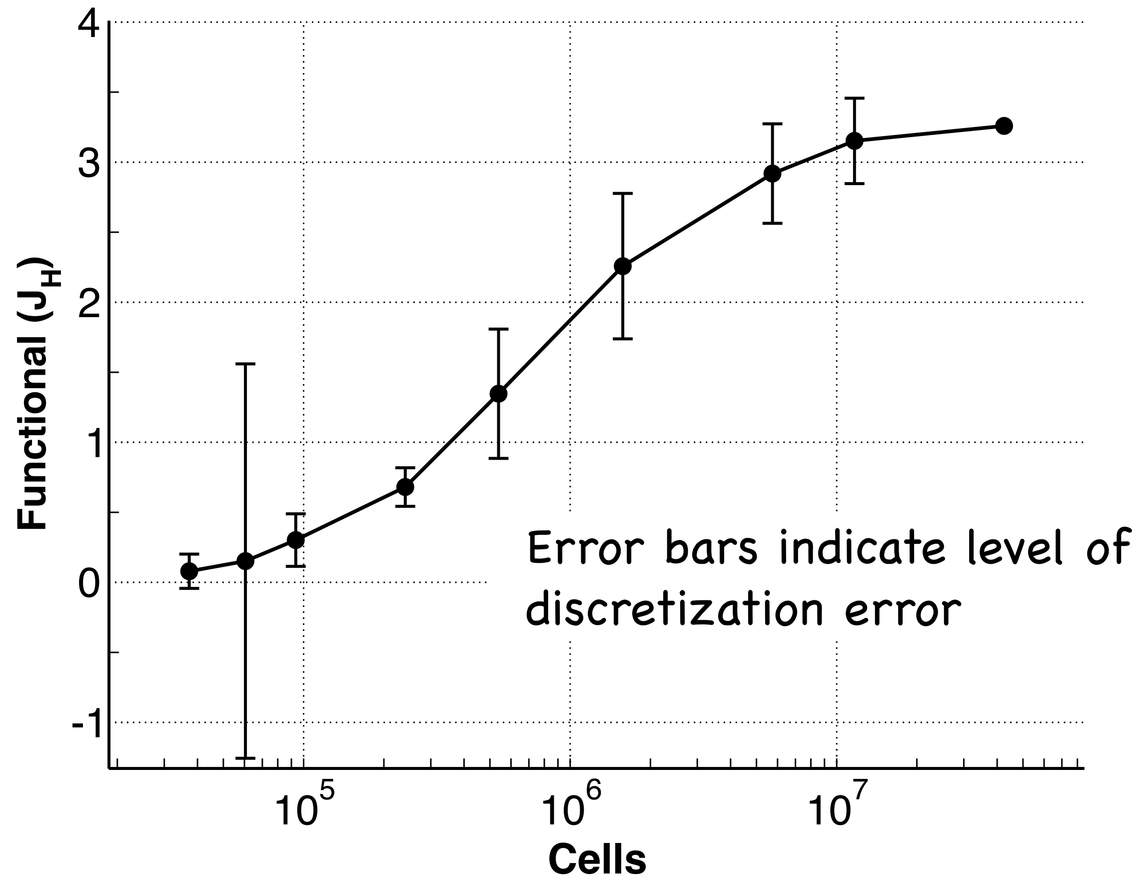


Nearfield Solution Quality



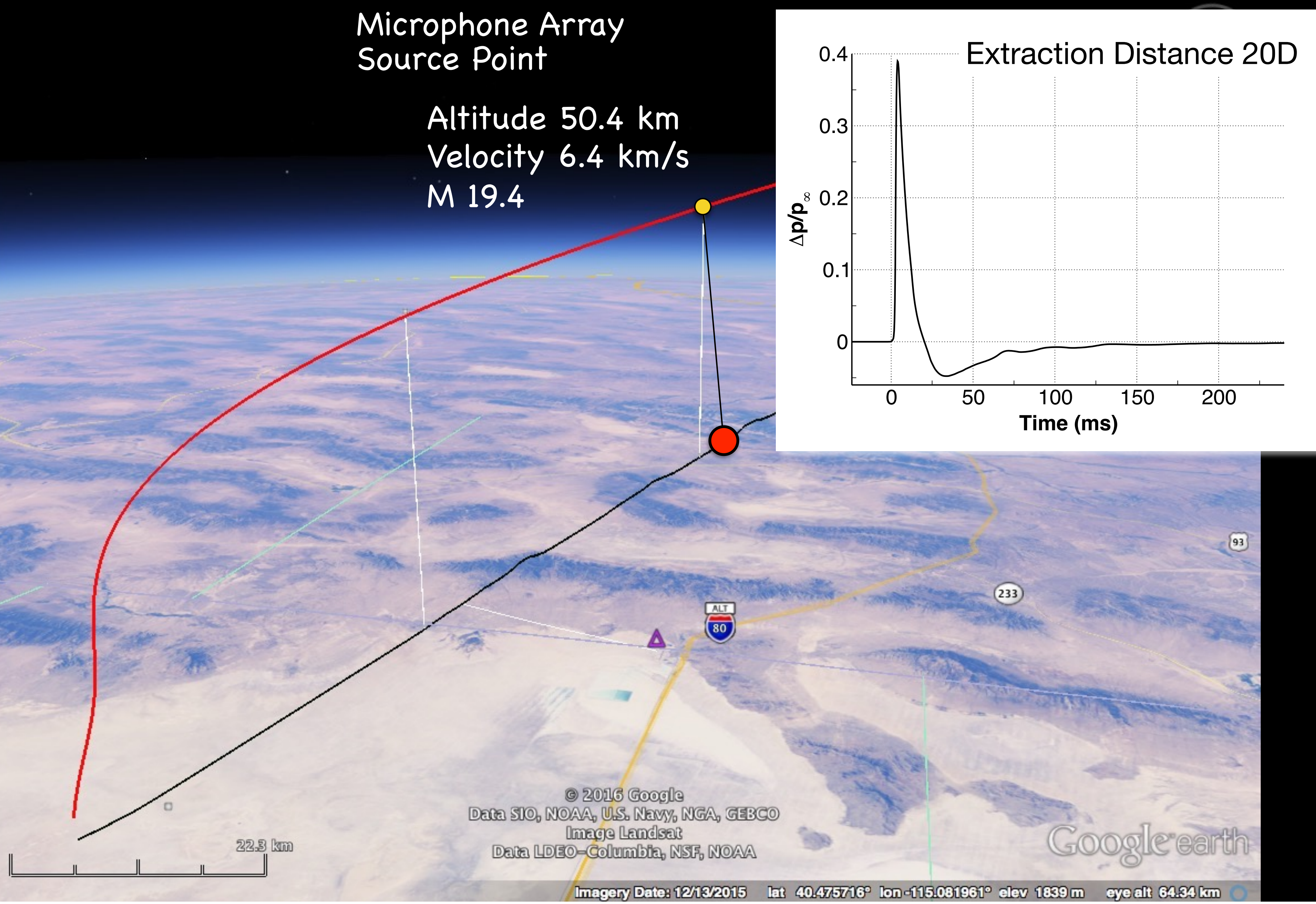


Output of Interest $J = \frac{1}{p_\infty^2} \int (p - p_\infty)^2 dS$

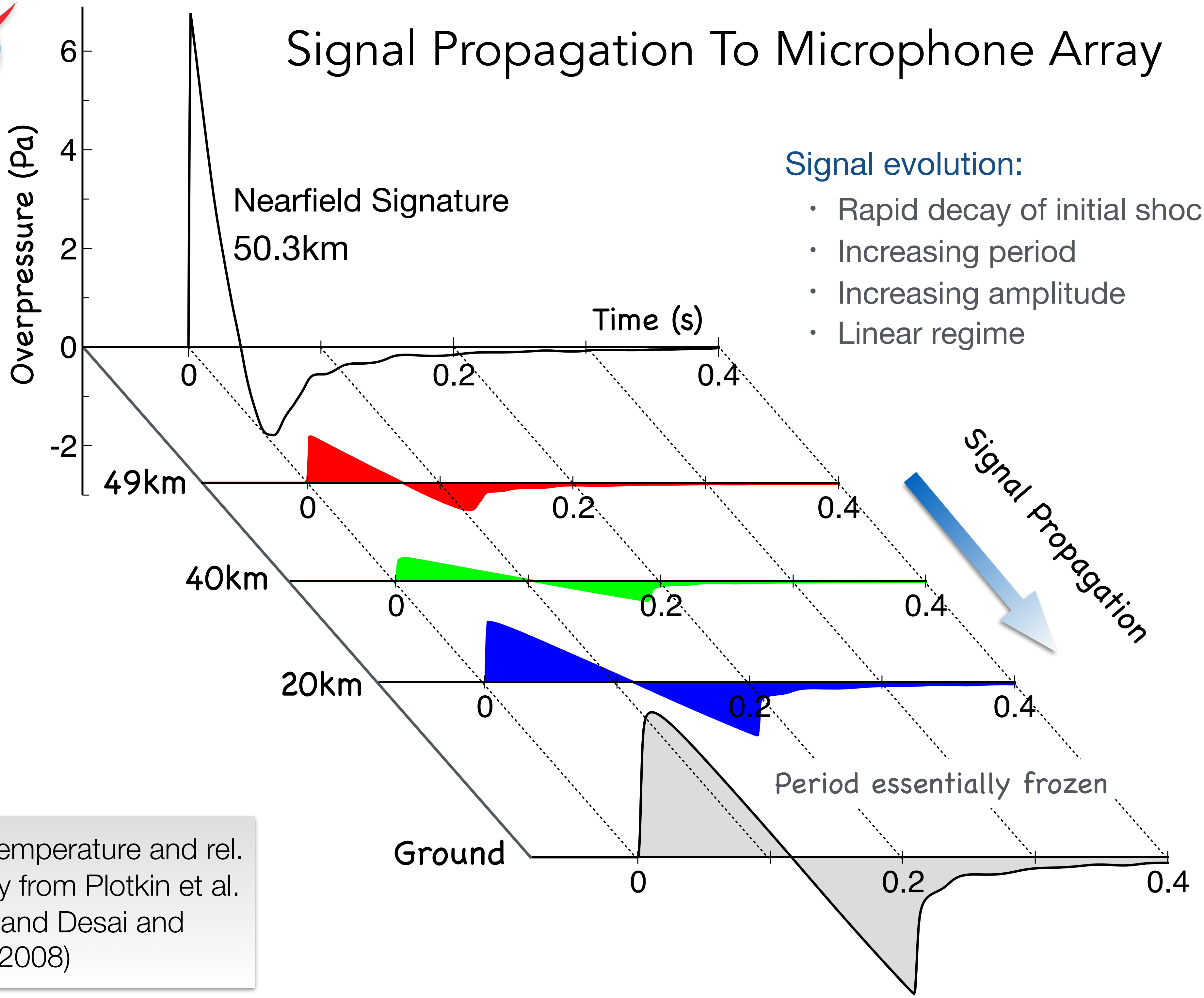


Mesh Convergence Study
(Line Sensor at 20D)

Nearfield Signatures



Signal Propagation To Microphone Array

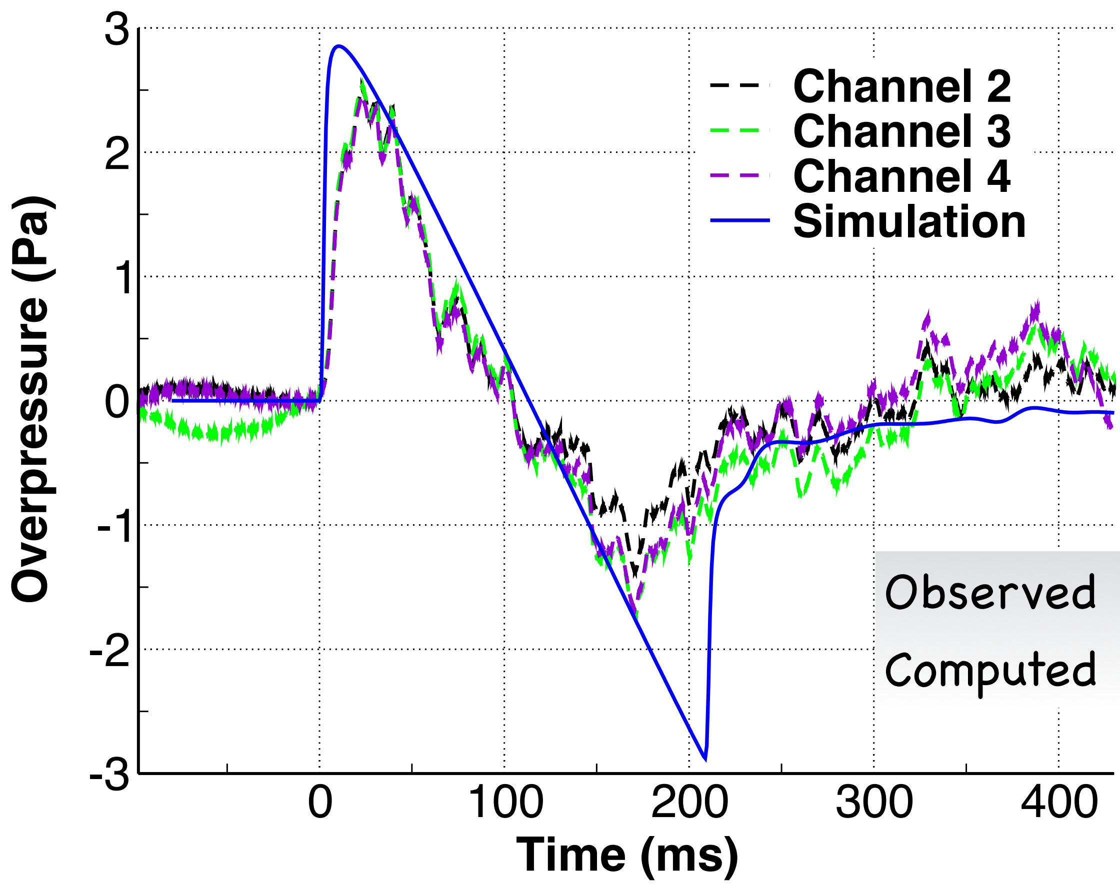


Signal evolution:

- Rapid decay of initial shock
- Increasing period
- Increasing amplitude
- Linear regime

Wind, temperature and rel. humidity from Plotkin et al. (2006), and Desai and Qualls (2008)

Microphone Array Comparison



M 19.4

Speed 6.4 km/s

Off-track 4°

Altitude 50.4 km

Observed travel time: 161 s

Computed travel time: 162.6 s

- Excellent prediction of period and amplitude
- Measured signature more asymmetric (expansion not as deep)

Data: Plotkin et al. (2006)

Atmospheric conditions: Plotkin et al. (2006), Desai and Qualls (2008) and ReVelle and Edwards (2007)

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    - Single infrasonic arrival
    - Low entry angle at 15.8 km/s
2. Meteor 20090428
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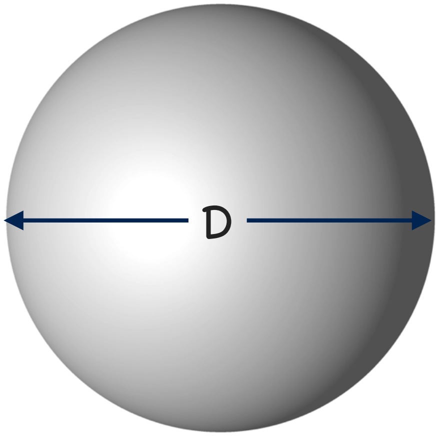
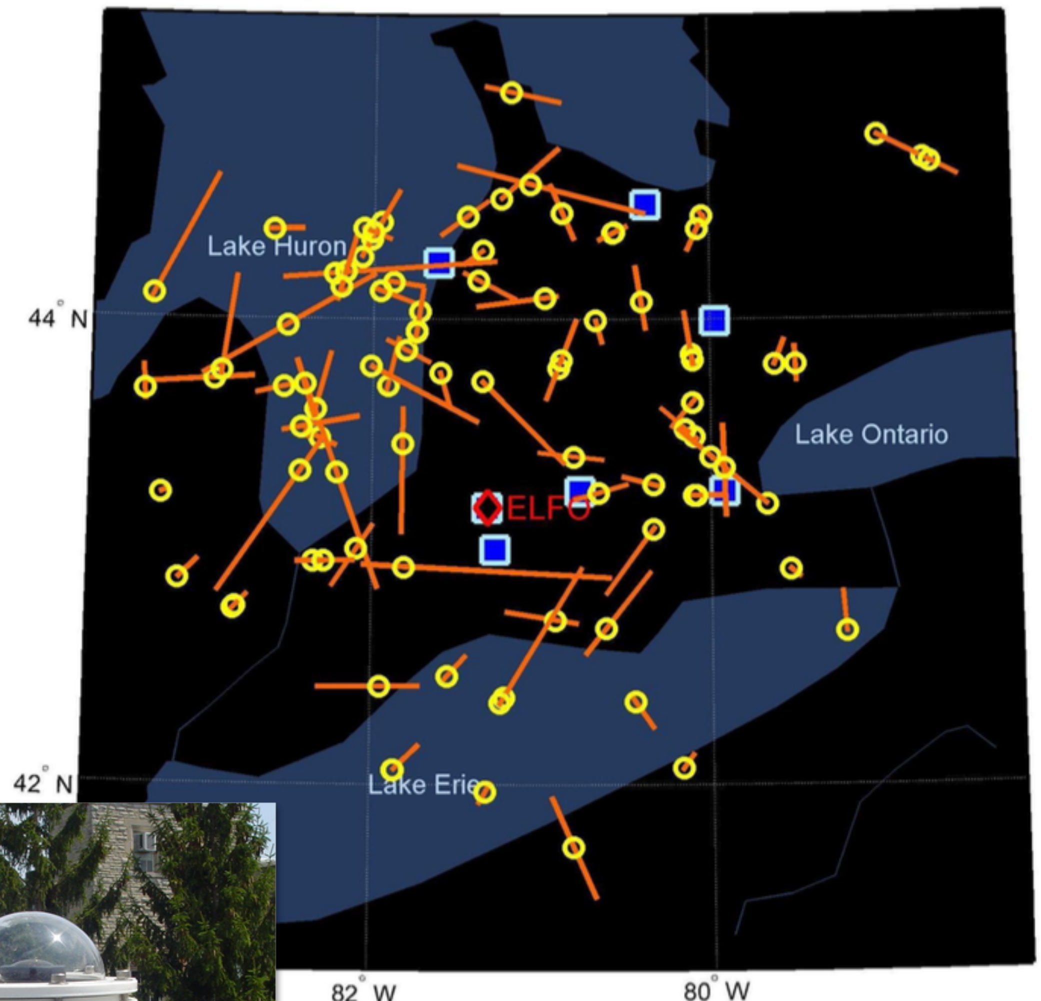


Meteoroid geometry

Southern Ontario Meteor Network

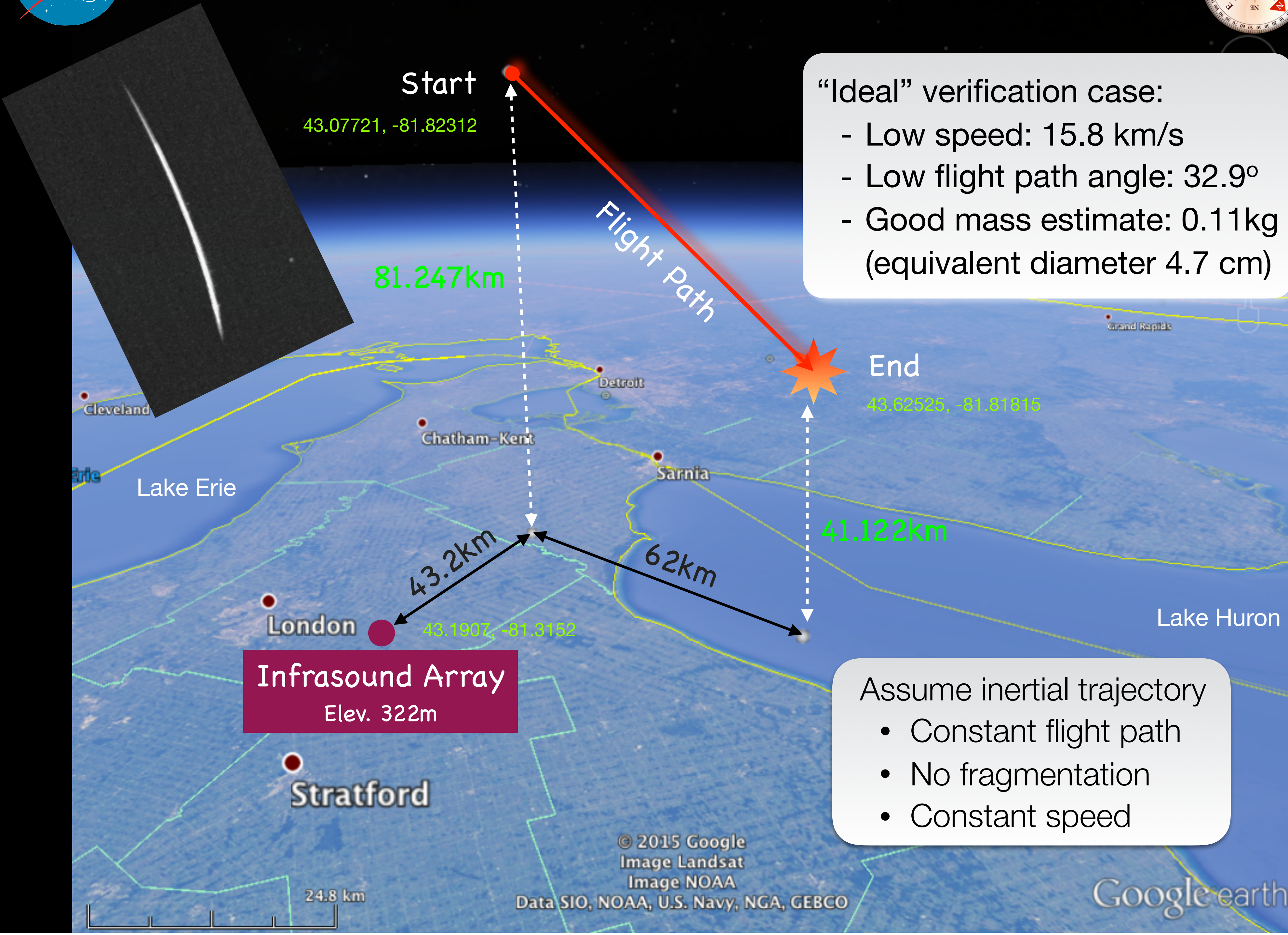
- Integrated optical and infrasound instruments
  - All-sky camera network (7—14 stations)
  - Elginfield Infrasound Array (ELFO)
- Between 2006–11: 6,989 meteors with 80 infrasound signatures

ELFO Map: All Events



Silber & Brown, J. Atmospheric and Solar-Terrestrial Physics, 2014

Meteor 20081028 Photometry Data



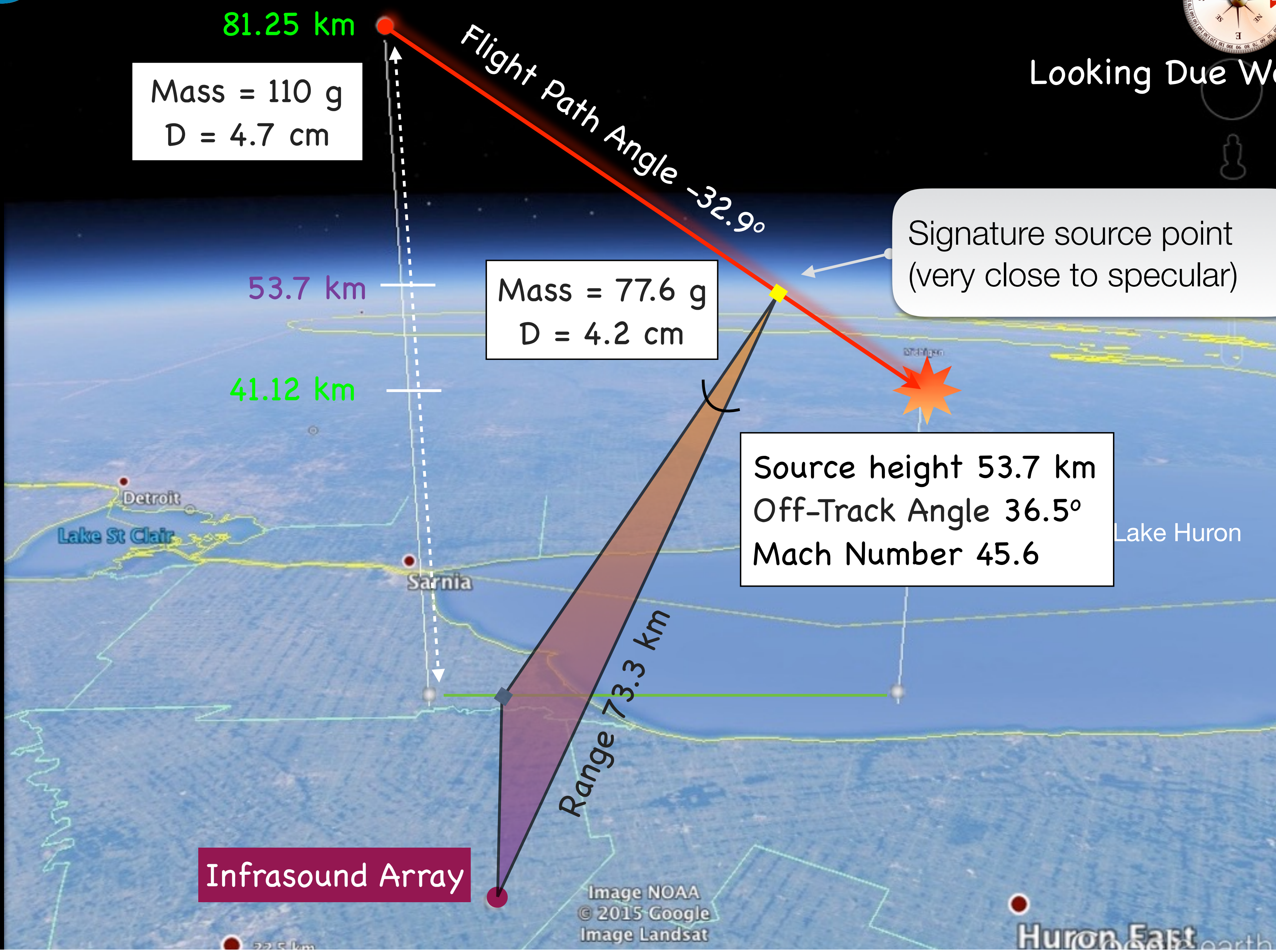
"Ideal" verification case:

- Low speed: 15.8 km/s
- Low flight path angle: 32.9º
- Good mass estimate: 0.11kg (equivalent diameter 4.7 cm)

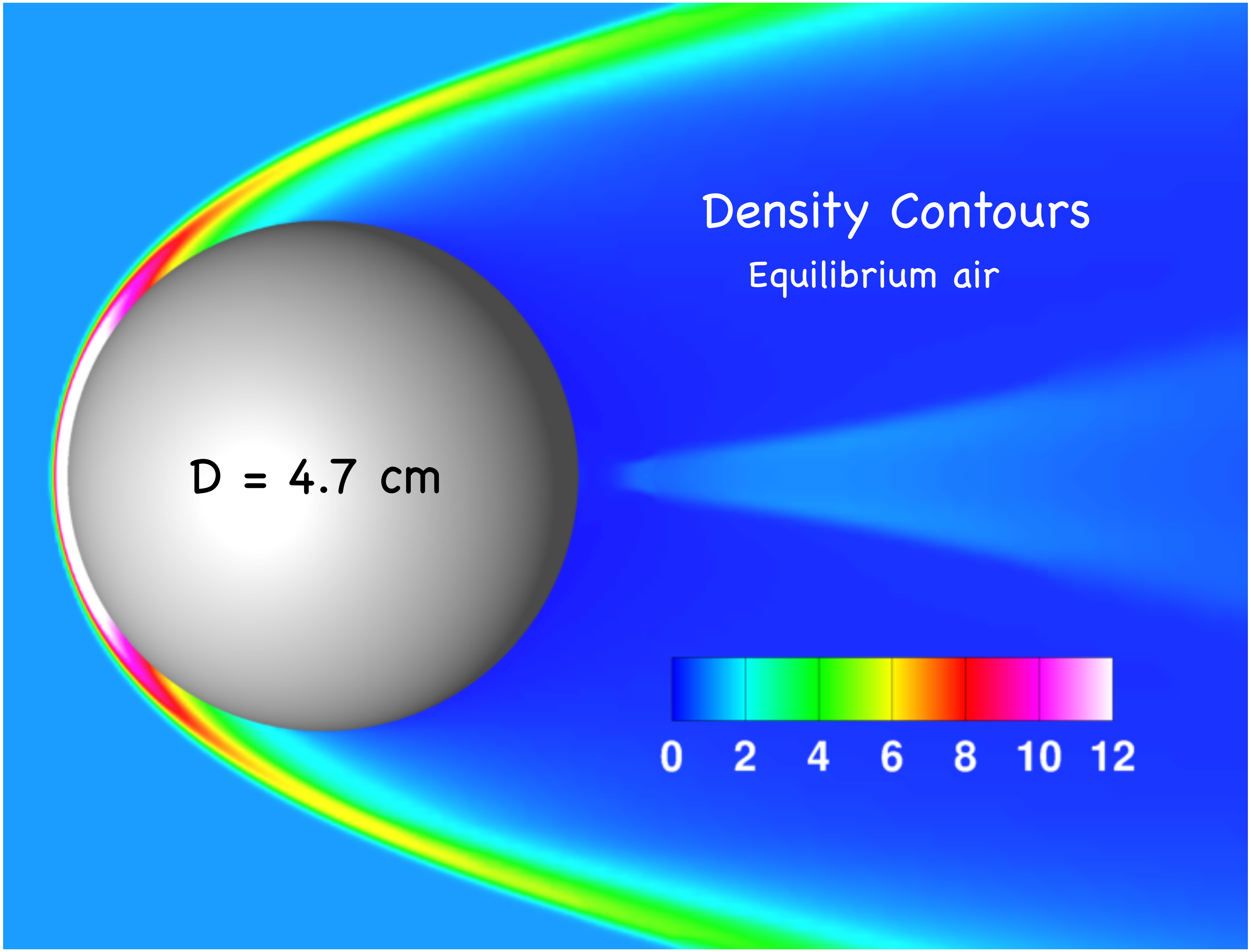
Assume inertial trajectory

- Constant flight path
- No fragmentation
- Constant speed

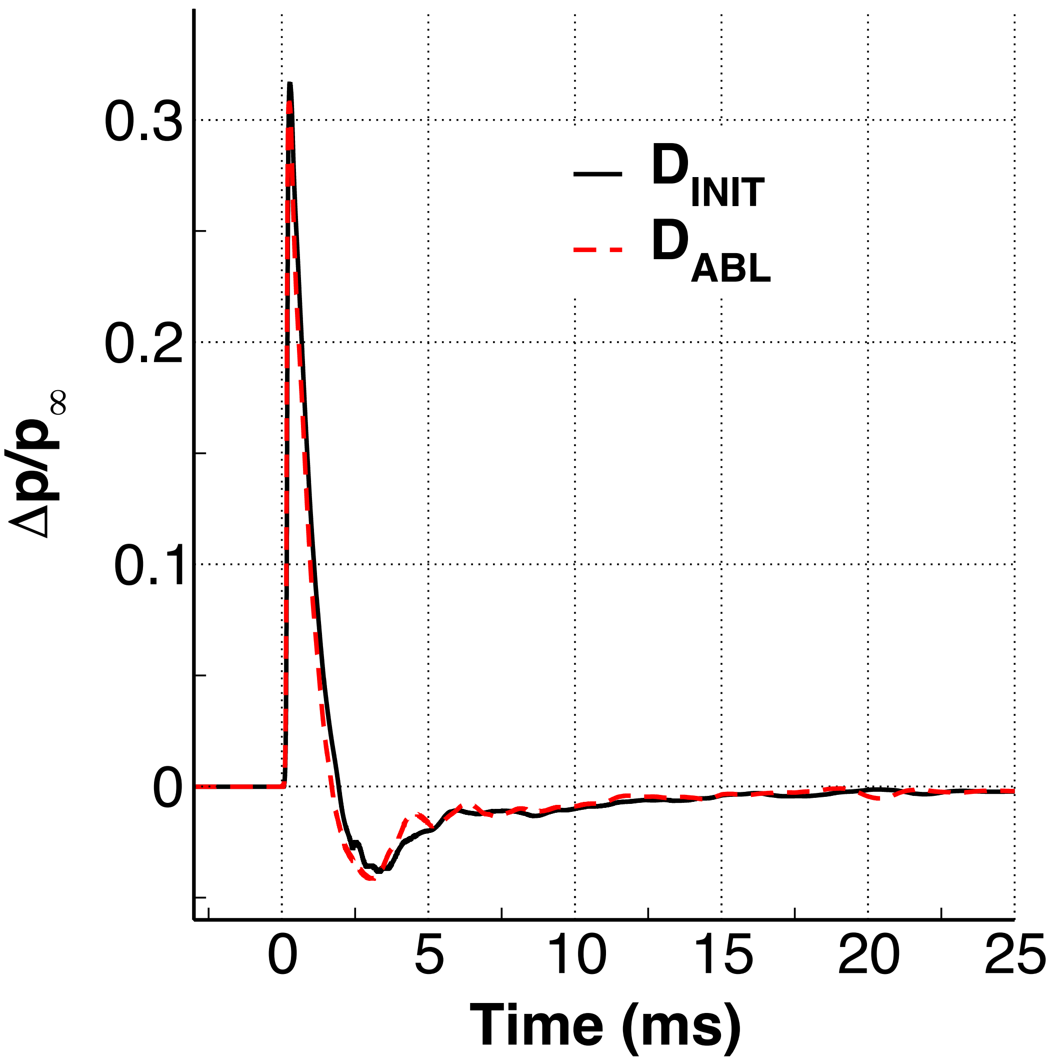
Trajectory Overview and Source Height



Near-body Flow Solution (M=45.6)

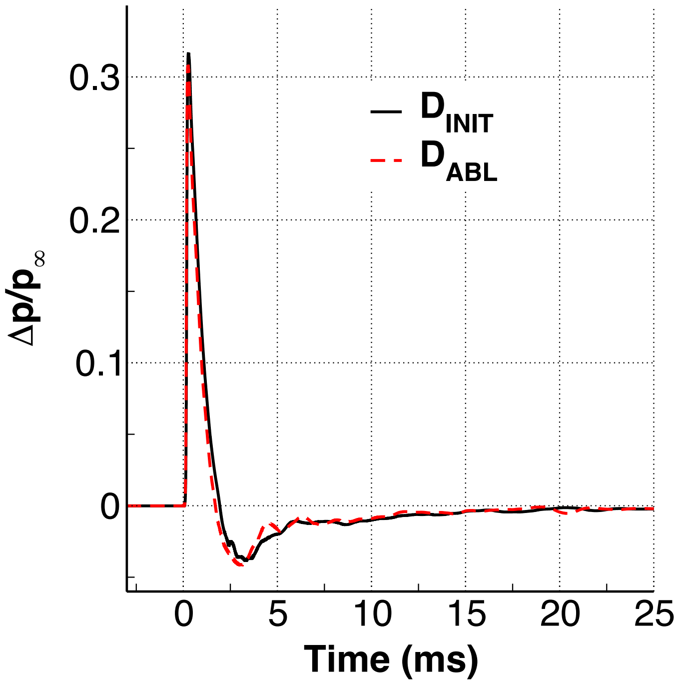


Meteor 20081028: Near-body Signature

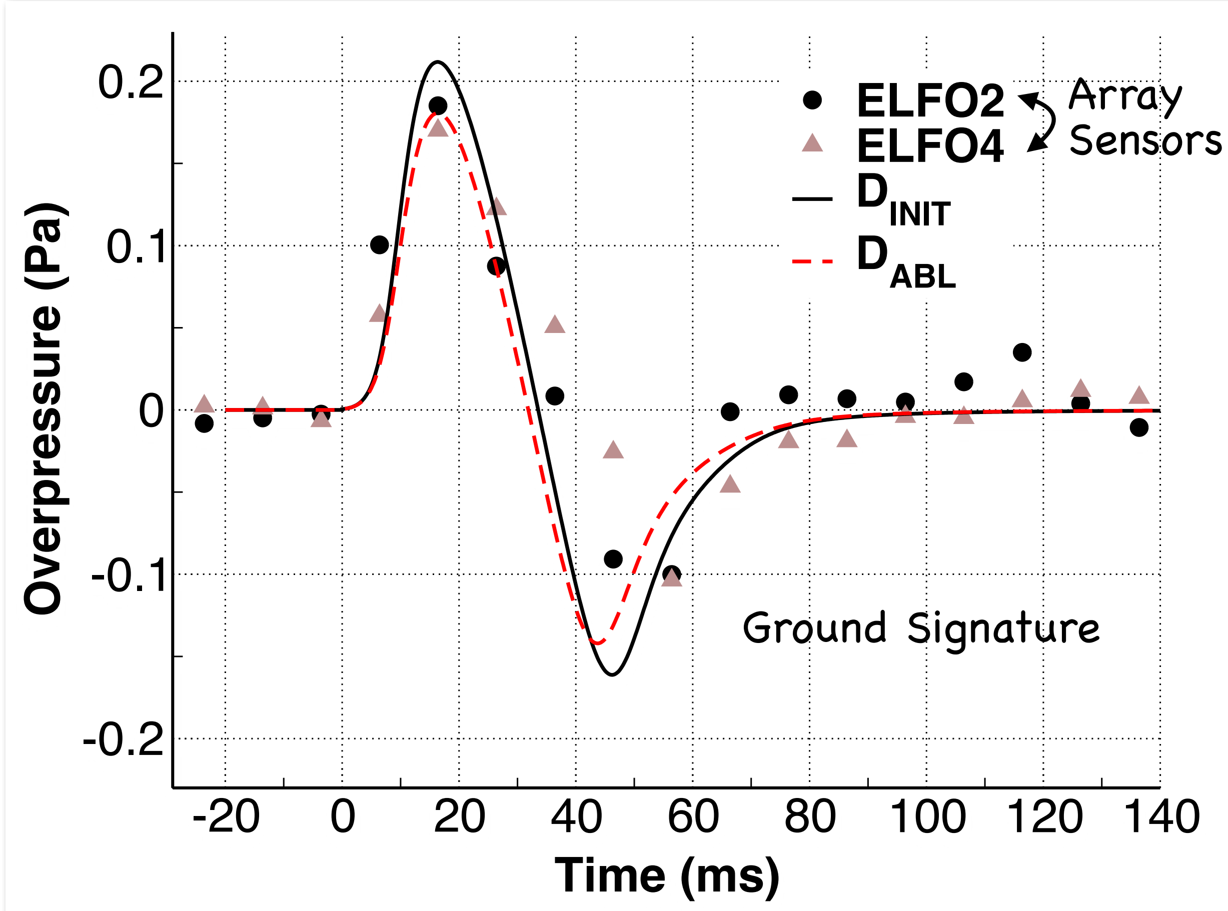


- Extraction distance 40D
- Pressure signatures for initial (D=4.7 cm) and ablated (D=4.2 cm) shapes very similar
- Larger body generates a slightly larger overpressure peak (<5%) and slightly larger time to zero-crossing

Comparison with ELFO Observations



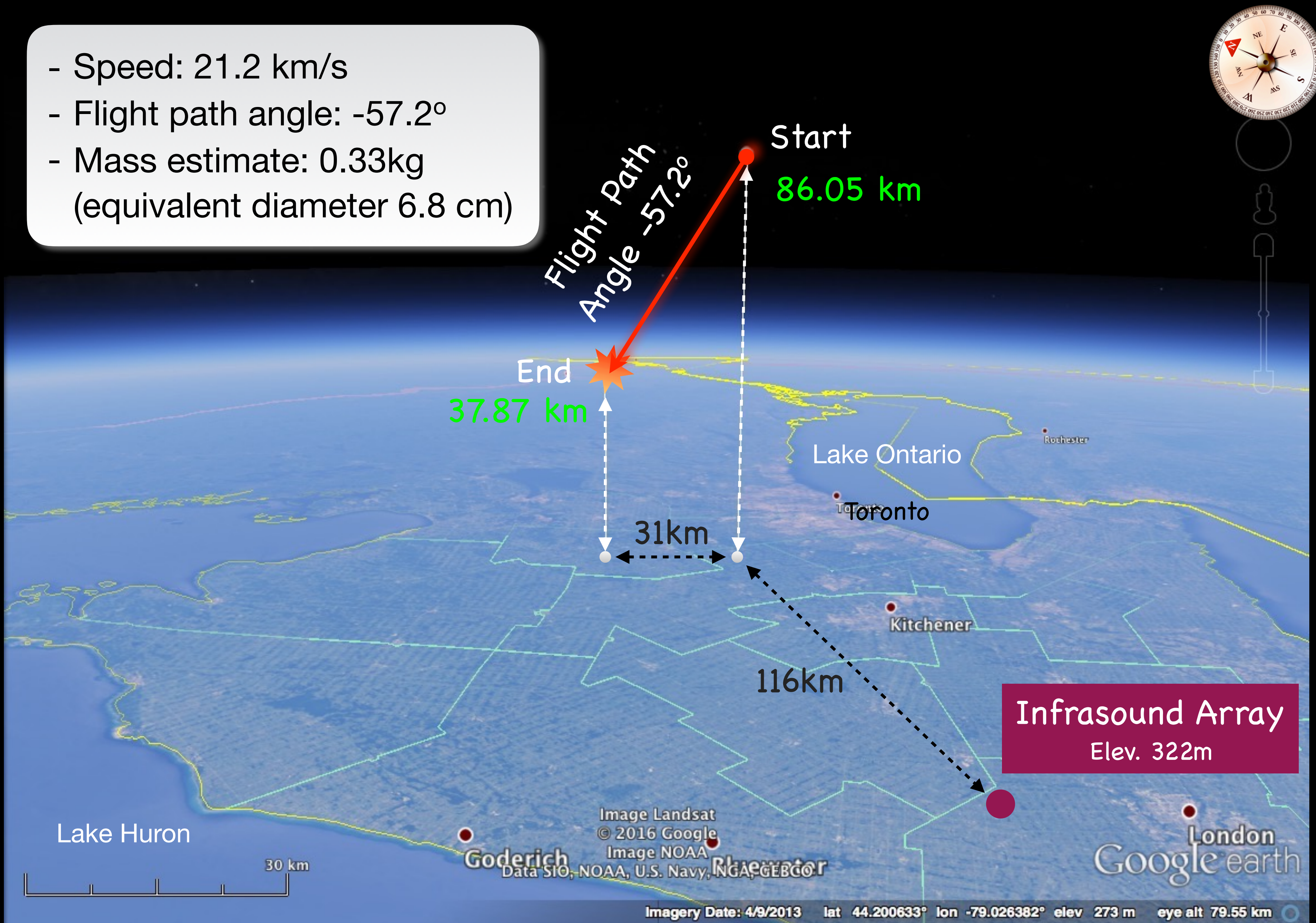
Near-body Signature



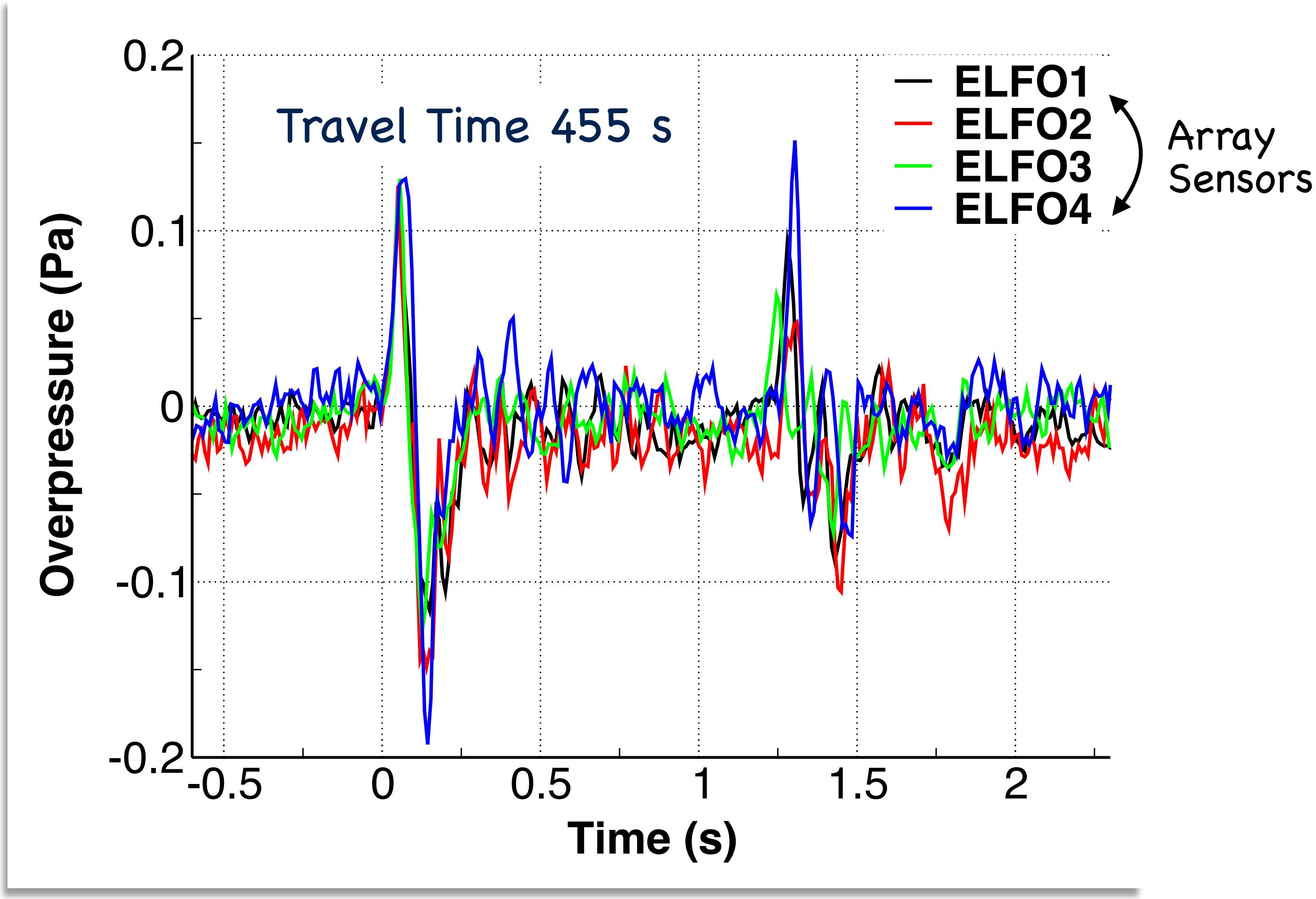
- Excellent prediction of amplitude, rise time, positive-phase duration and period
- Validates photometric mass estimate

Meteor 20090428 Photometry Data

- Speed: 21.2 km/s
- Flight path angle: -57.2°
- Mass estimate: 0.33kg (equivalent diameter 6.8 cm)

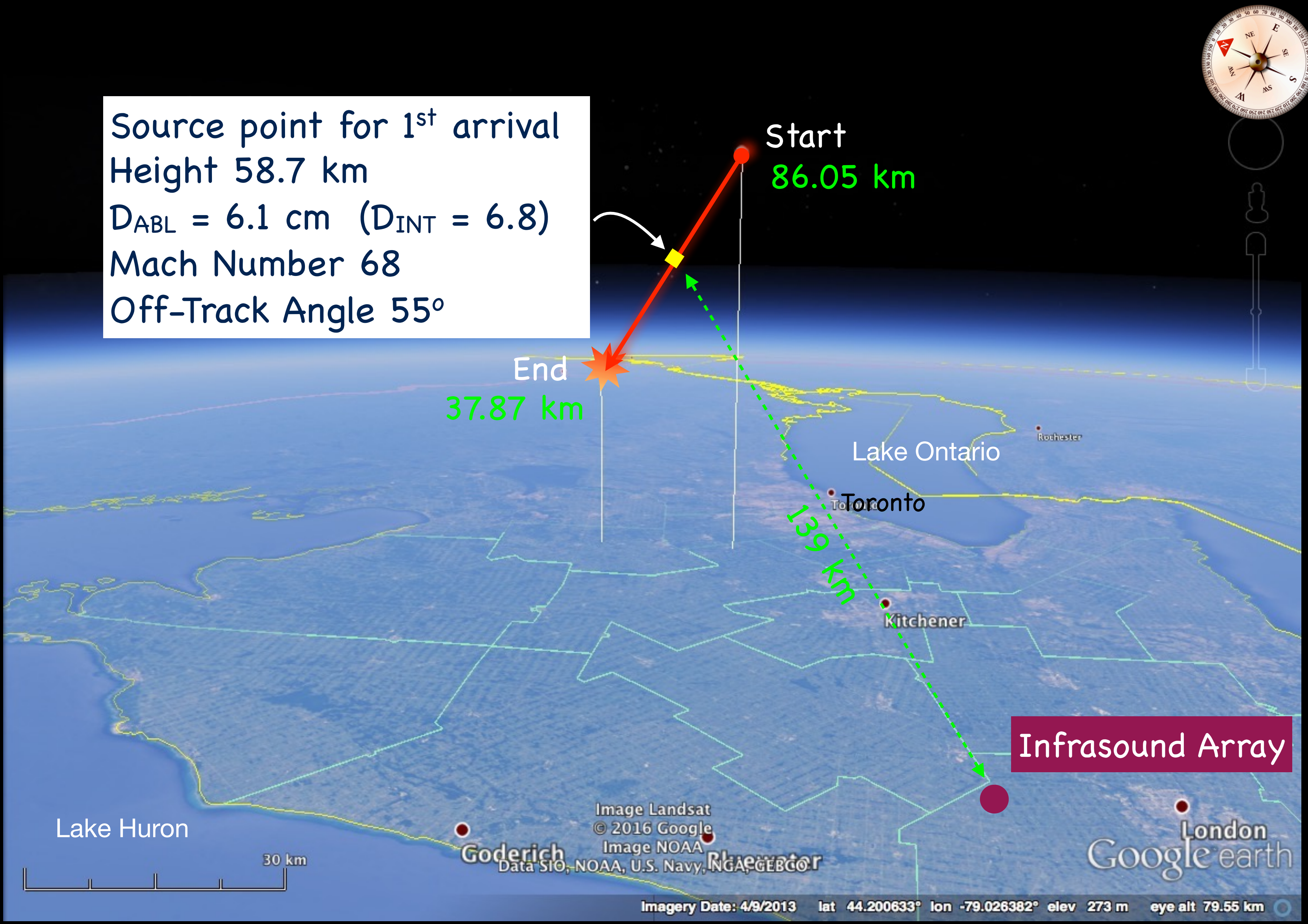


SOMN Observations

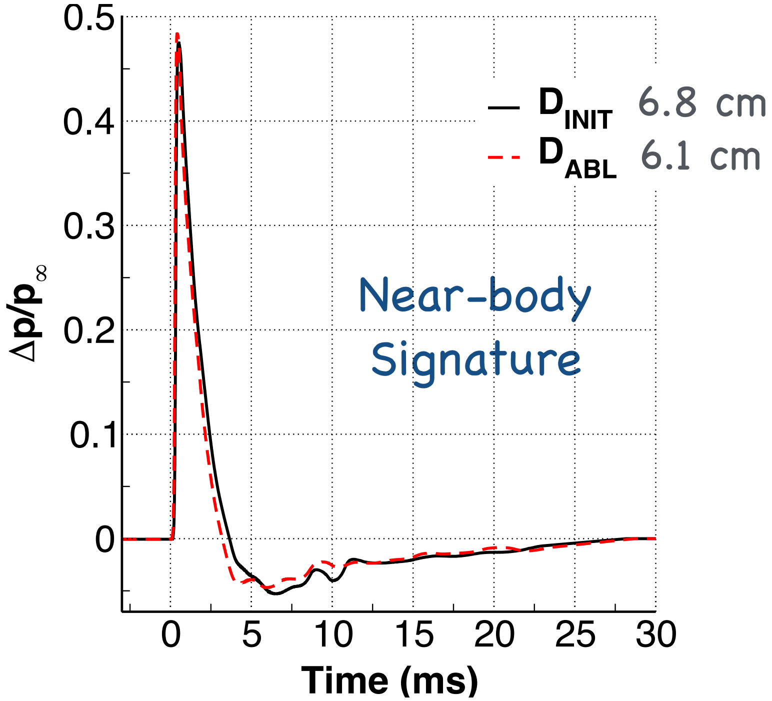


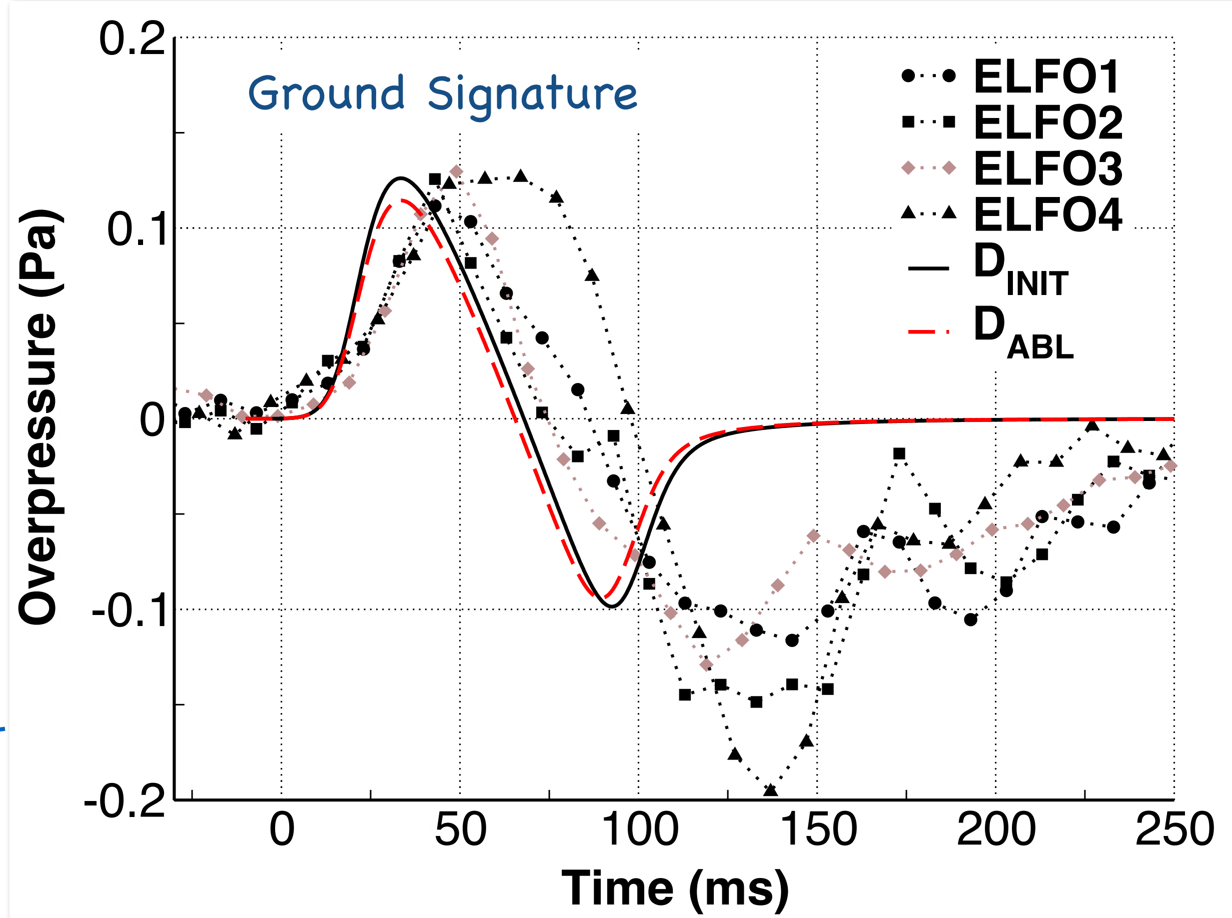
- Sensors show 2 distinct arrivals
  - Assume one is from cylindrical Mach-cone while the other is from fragmentation
  - Can simulation help identify the specular arrival, i.e. the one from the cylindrical Mach cone?

Meteor 20090428 Ray Tracing Results



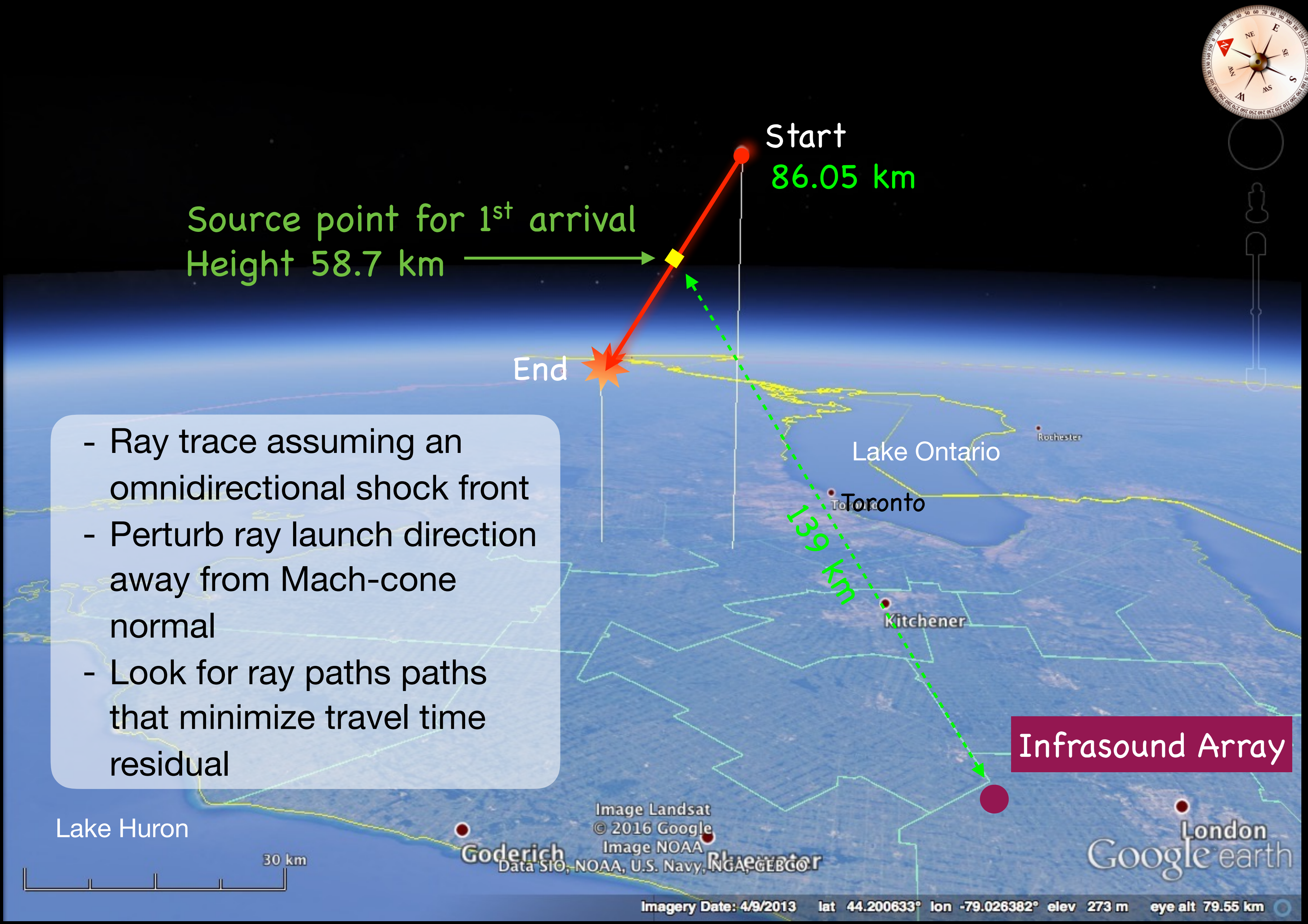
Comparison with ELFO Observations — First Arrival





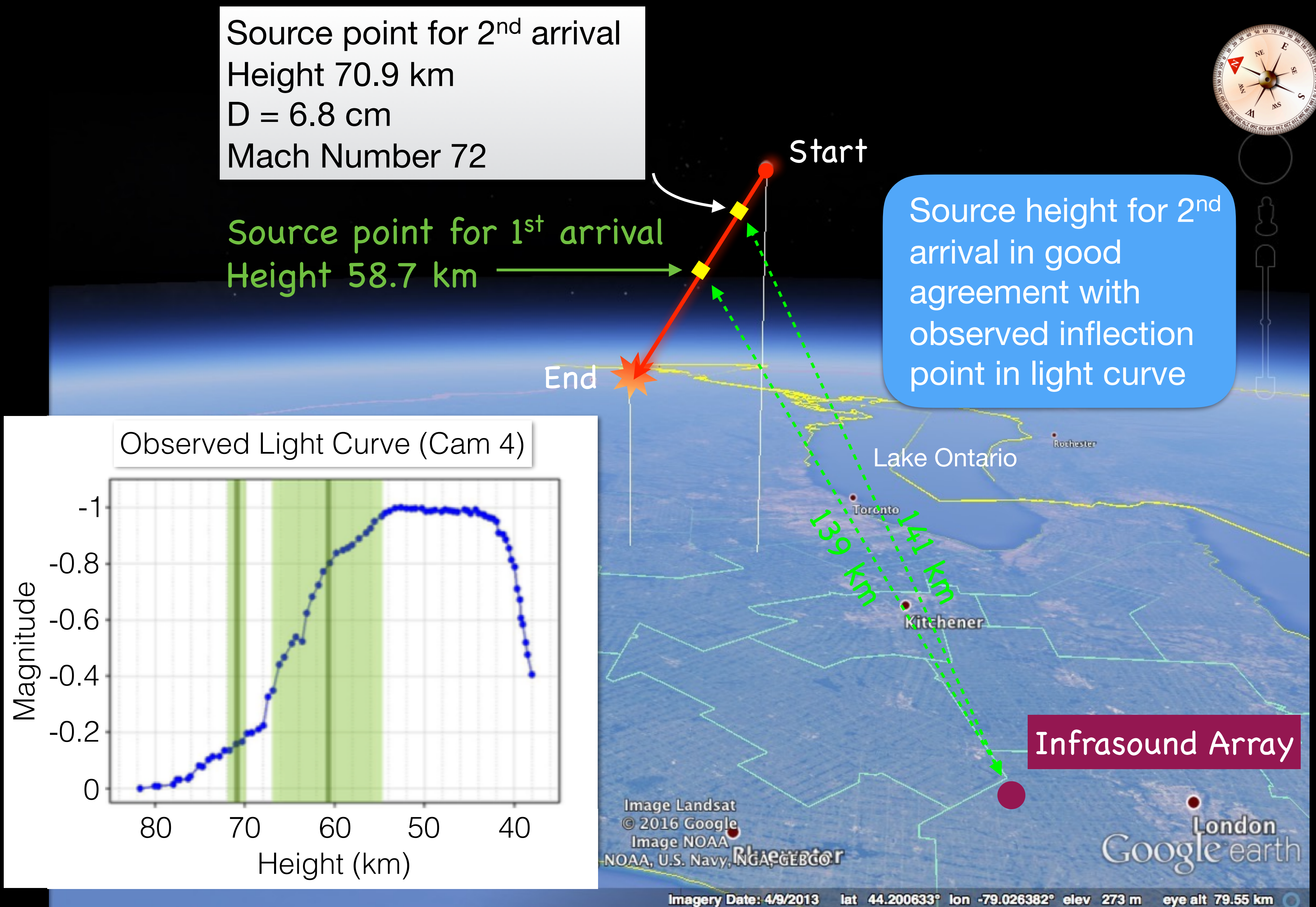
- Excellent agreement in amplitude
- Rise time under-predicted, but positive-phase within 8% for 2 out of 4 sensors
- Poor agreement in trailing recompression —limitation of spherical shape assumption

Meteor 20090428 — Second Arrival



- Ray trace assuming an omnidirectional shock front
- Perturb ray launch direction away from Mach-cone normal
- Look for ray paths paths that minimize travel time residual

Meteor 20090428 — Second Arrival

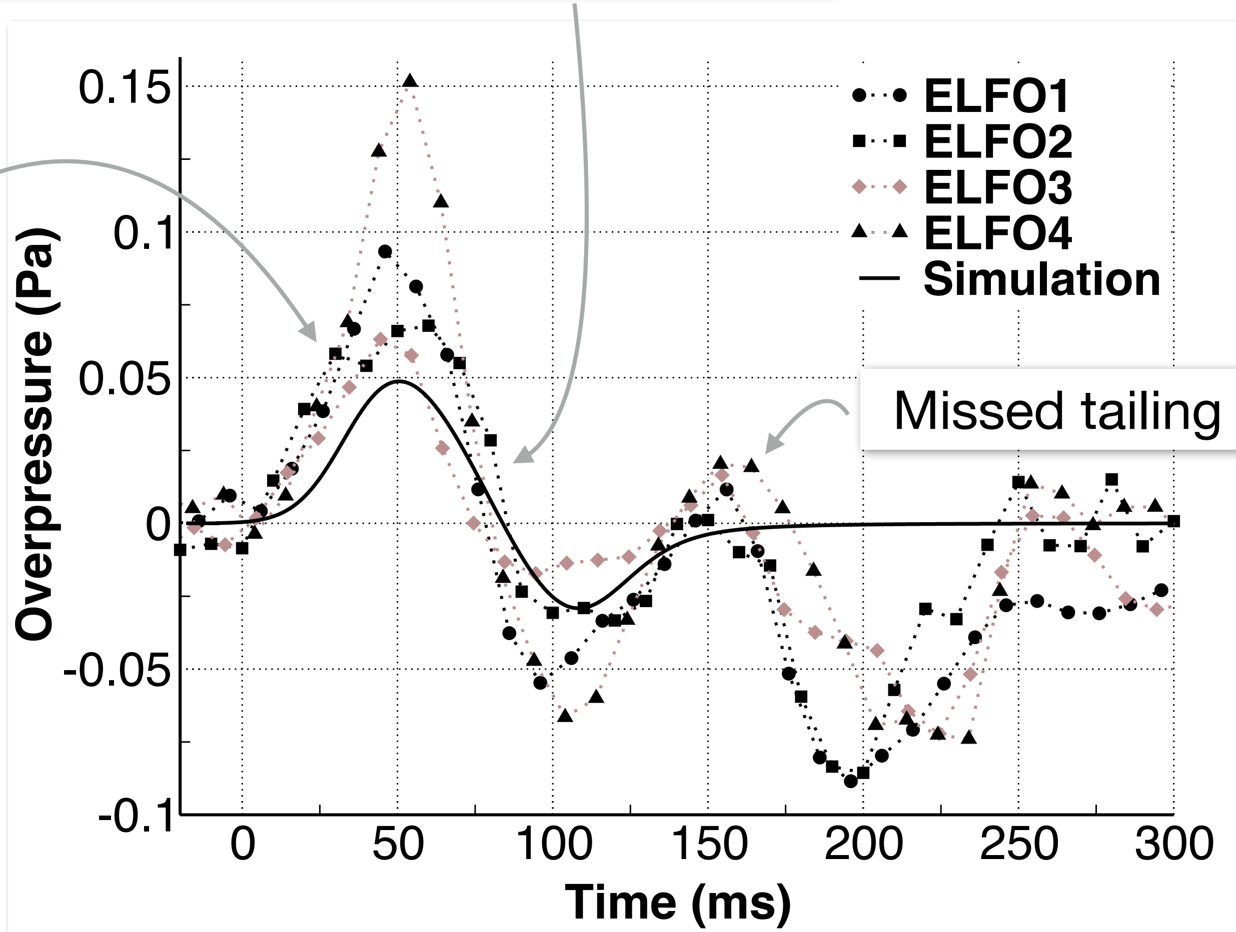


Comparison with Observations — Second Arrival

Rise time and positive-phase duration predicted well

Amplitude within a factor of 2

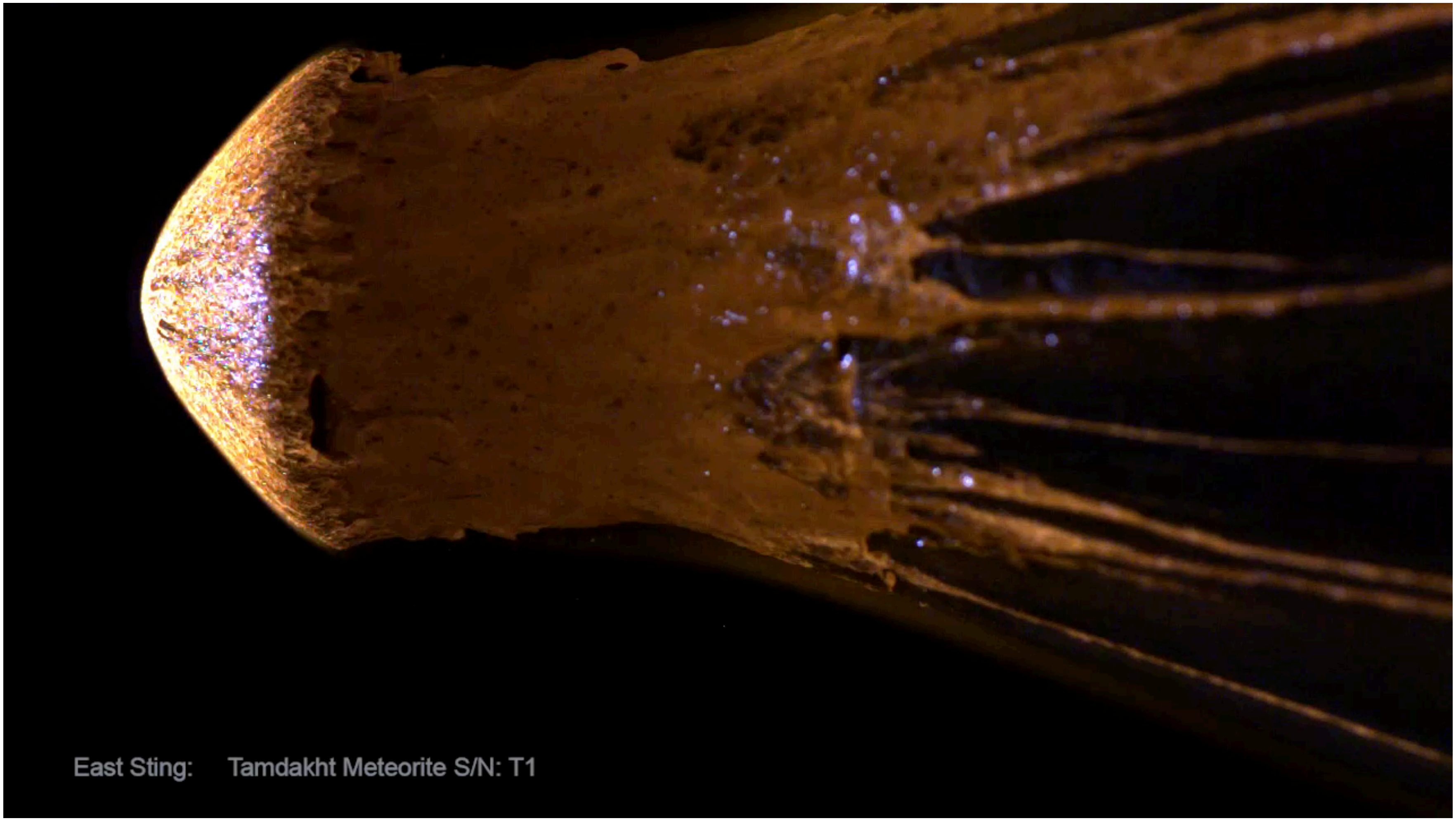
Missed tailing wave-train



- Signature source appears to be cylindrical Mach cone with fragmentation
  - Onset of melt?
  - Partial disintegration at high altitude affects first arrival

Quasi-Continuous Fragmentation

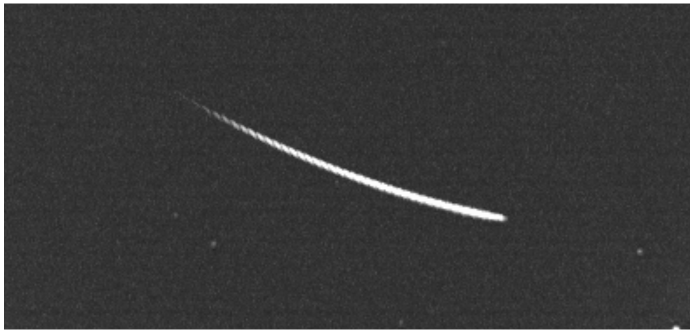
Meteoroid Ablation Experiments

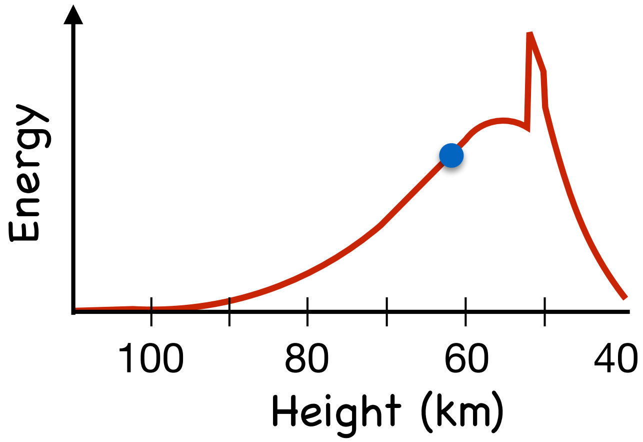


- NASA Ames Arc Jet
- 4 kW/cm^2 (~60 km altitude, 20 km/s), Stern et al., 2017

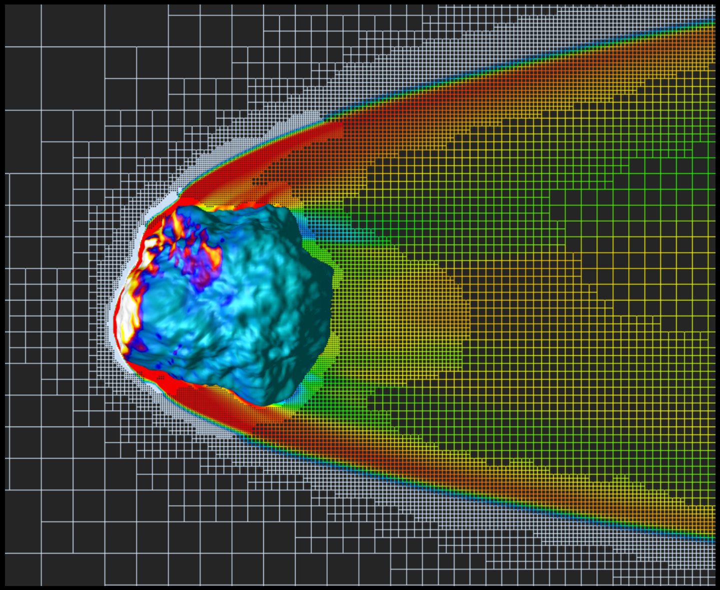
Summary

- Adapted aircraft sonic-boom analysis to the prediction of meteoric infrasound
- Used Stardust entry to verify proposed approach
- First direct comparison of simulations with infrasound measurements:
  - Excellent agreement in zero-peak amplitudes, rise times and positive-phase duration
  - Results verify mass estimates deduced from optical observations
- Improvements needed in prediction of trailing waveform
  - Sensitivity to meteoroid shape and multiple bodies
  - Higher-fidelity CFD modeling of wake
  - Modeling of attenuation and dispersion of low frequency signals





Future Work



- Explore signatures from various meteoroid shapes and configurations with multiple bodies
- Investigate solvers appropriate for transitional regime to accommodate higher source heights

Acknowledgements

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Questions

http://www.cnn.com/2016/03/04/world/scientists-drill-impact-crater-irpt/index.html